Awareness, Perceptions and Willingness to Adopt Cross-Laminated Timber in the United States

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Dedication

To my grandmother.

Abstract

One of the most recent innovations in Engineered Wood Products is Cross-Laminated Timber (CLT). The system is based on the use of multi-layered panels made from solid wood boards glued together, with the grain direction of successive layers placed at 90° angles. The cross-laminated configuration improves rigidity, dimensional stability, and mechanical properties. Structurally, CLT offers performance comparable to concrete or steel, with panels suitable for use as walls, floors, roofs, and other applications.

While CLT as a construction material has been successful in Europe for the past 20 years, and more recently has made inroads in the Australian and Canadian markets, it is not yet readily available in the United States. To better understand the market potential for CLT in the U.S., this study aims to assess the level of awareness, perceptions and willingness to adopt the system by U.S. professionals. To achieve these objectives, (a) a series of 10 interviews were conducted to gather insights from national and international CLT experts; (b) a web-based survey to U.S. architecture firms was conducted to gather information about familiarity, perceptions, performance and likelihood to adopt the system in the near future; and (c) a multi-family residential building project was designed to explore the architectural possibilities of the material.

This study identified that the use of wood, a natural and renewable material, was the main advantage of CLT. Another important benefit of CLT over traditional construction systems is the dramatically shorter on-site construction time needed. CLT is a prefabricated system, thus reducing labor requirements, on-site waste, and accidents, all of which translates into significant cost reductions. The most commonly cited disadvantages of CLT were its acoustic and vibration performance. From the study it was found that the level of awareness about CLT is low among U.S. architects. Building Code compatibility, availability in the domestic market and cost were mentioned as the main barriers to the implementation of the system in the U.S. Cross-Laminated Timber appears to be a cost-competitive alternative to concrete structures, especially for buildings over six stories high. Architects seem to be willing to adopt CLT for their near-future projects, especially for multi-family, commercial, and recreational buildings. Importantly, this willingness to adopt CLT was found to be positively correlated to the level of awareness with the system. Results show that diffusion of knowledge about CLT and the role of early adopters will be essential for the successful introduction of this new building technology into the U.S. market.

The preliminary design created as part of this study allowed demonstrating the structural capabilities of CLT, by maximizing the spans between structural elements achieving open and fluid living spaces. CLT also enabled the design of wide terraces and the inclusion of window openings on outside walls without compromising the structural integrity of the CLT elements.

Keywords: Cross-laminated timber (CLT), massive timber, engineered wood products, sustainable buildings, wood-based construction.

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Chapter 1
Introduction and Literature Review

Wood has played an essential role in the development of civilization (Ritter et al., 2011), providing heat, energy, transportation and shelter for millennia (Perlin, 2005). Wood's intrinsic characteristics make it remarkably flexible and versatile, as being demonstrated by the wide variety of successful applications. Wood is widely available, is renewable, and easy to transform. Particularly, the outstanding structural (exceptionally strong relative to its weight) and environmental performance in comparison to concrete or steel and its pleasuring aesthetics (CEI-Bois, 2010; Howard et al., 2011) have made the construction industry the main driver for demand of forest products.

More recently, the growing concern for environment degradation, climate change, and energy independence, has led to a fresh consideration of wood as construction material (Omer, n.d.). Many programs to promote wood-based construction have been implemented in parts of the world to promote this shift towards more environmentally-conscious building construction (Tykkä et al., 2010; Jackson, 2013). The Nordic Wood Program started in Europe in 1995 focused on the development of multi-story wood residential construction (Dragheim et al., 1999; Thelandersson, 1997). Another project that focused in the use of wood as a building material is the Finnish "Modern Wooden Town" (Tykkä et al., 2010). The goal of this project was to explore the construction of a new type of dense wooden town based on the old finish wooden town tradition (Jari et al., n.d.). The Norwegian Wood Research Institute carried out a program to develop timber construction by testing new ideas through practical building projects from 2004-2008 (Norwegian Wood Research Institute, 2011). The Swedish government commissioned comprehensive research on the county's wood industry situation and its position in the international market. The study was published in 2004 as a national strategy to promote wood construction and renew the Swedish wood industry (Falk, 2005). Years later the Swedish project Trästad 2012, also known as "Wood City 2012" was created. This last project is a cooperative study between municipalities and county administrative boards, which focuses on sustainable urban development based on wood based construction (Claar, 2012).

Governmental initiatives have been also developed in the U.S. Specifically, the Department of Agriculture's Forest Service is exploring new ways to increase research on areas related to the development of green building materials, while establishing its preference to select wood-based materials in new building construction (especially federal government facilities and buildings) and maintaining its commitment to green building standards (USDA, 2011). The Forest Service is also encouraging the use of renewable biomass such as wood to fuel power generation plants (USDA, 2011). The forest products industry is an important sector of the U.S. economy (it is among the top ten manufacturing employers in 47 states). Each year the process of harvesting wood, manufacturing and use of timber in construction generates over a million jobs, contributing to six percent of the U.S. manufacturing Gross Domestic Product (USDA, 2014).

Attitudes towards timber construction

According to a survey regarding consumers' attitudes towards wood as a construction material performed by Gold et al. (2008), the most decisive criteria for choosing a construction material are: appearance, comfort and health issues (e.g., allergy prevention and air quality). Wood is typically perceived as performing well in these categories, thus people in general are prone to have a positive attitude towards wood as a construction material (Bringslimark et al., 2009; Høibø, 2010). Other important criteria when choosing building construction materials are factors such as quality, structural and environmental performance, fire resistance, maintenance and costs (Gold et al., 2008; Bysheim, 2008). Regarding those issues, the study shows, people still have doubts, especially when it comes to fire performance, maintenance cost, and initial cost of wood constructions (Gold et al., 2008; Kirkegaard, 2012).

Another study was conducted by Roos et al. (2010), to gain insights on building professionals' (architects, engineers and contractors) perceptions of wood constructions (Roos et al., 2010). Results showed that the main advantages of wood mentioned by respondents are in regards to the aesthetic qualities, pleasant indoor climate and atmosphere, as well as its strength-to-weight ratio and energy efficiency (Roos et al., 2010). Several disadvantages of wood were also mentioned, with wood's dimensional stability related to changes in moisture content and sound transmission properties being the most important (Roos et al., 2010; Schickhofer et al., 2006). Roos' study (2010) also shows skepticism and prejudice when it comes to the technical performance of the material.

Wood engineered products

Despite its many advantages, the use of wood as a building material is not free from challenges. Wood is a natural material, its properties are not homogeneous, and vary widely depending on genus, species (variations exists because of environmental and genetic influence) and composition and arrangement of wood cells within each tree (Forest Products Laboratory, 2010). To address wood's variability and better utilize the material, Engineered Wood Products (EWPs) were developed. These products are manufactured to achieve targeted engineering properties, such as high performance, reliability, consistency. EWPs also help utilize forest resources more efficiently (Forest Products Laboratory, 2010). Manufacturing techniques, mechanical evaluation, and special connectors and adhesives are used to increase the loading strength capability of EWP elements.

According to the Canadian Wood Council (n.d) engineered wood products differ from visually graded sawn lumber products in a number of ways. First, the manufacturing processes for engineered wood products generally require that wood has a moisture content of less than 15%, which results in a material more dimensionally stable and less prone to shrinkage. Second, EWPs are subject to structural properties qualification testing and daily quality control, which makes them more reliable and predictable than solid wood (Forest Products Laboratory, 2010).

Innovation in the field of EWPs has seen rapid growth in recent decades (FAO, 2012). Designers and builders are attracted to the strength, quality, and reliability of these products. Their higher purchase costs compared to solid lumber are usually compensated by ease of use in construction and increased final performance. Thanks to developments in this area, wood can now be used where once materials like steel or concrete were the only option, such long span applications.

One important development in wood construction in the twentieth century was the development of glued-laminated beams also known as Glulam, which represented an important advance in terms of being able to cross long spans (Canadian Wood Council, n.d.). Glulam beams are manufactured by gluing together mechanically and visually graded pieces of dimension lumber to produce much larger sections. In the manufacture of these elements, wood pieces are finger-jointed and arranged in horizontal layers or lamellas (Slavid, 2005).

The development of panel products also established new uses for wood in building construction (Slavid, 2005). Products such as plywood, Oriented Stand Boards (OSB), Medium Density Fiberboard (MDF), and particle boards have gained considerable market share during the last decades. One of the main advantages of these products beyond the reduced variability of the material is that they enable the use of lower quality wood to create value-added products (APA, 2014), resulting in a better utilization of the forest resource.

Another EWP, the I-joist, which is made by gluing solid sawn lumber or Laminated Veneer Lumber (LVL) flanges to a plywood or OSB web, to produce a dimensionally stable, lightweight structural element (Slavid, 2005; APA, 2014). The uniform strength of these structural components makes them well-suited to perform as long span beams (Canadian Wood Council, n.d.). I-joists also show a high strength-to-weight ratio. The moisture content of the elements present in the I-joist is low (around 10% MC), thus the tendency to shrink or warp is greatly reduced, which results in more stable structures (Canadian Wood Council, n.d.).

The strength, reliability and long span capability are attributes that make EWPs attractive alternatives to solid wood in most types of buildings. The variety of EWPs available in the market provides architects, engineers and builders with virtually limitless design possibilities.

Cross-Laminated Timber

One of the latest innovations in the area of EWPs has been the development of Cross-Laminated Timber (CLT), also known as “Cross-Lam”, “X-Lam” or “Massive Timber” (Podesto, 2011). CLT panels are strong and stiff, which allows them to be used in a wide range of applications (Ceccotti et al., 2010). The use of CLT panels has become a popular and successful method of construction in Europe since its introduction. It is currently used for all kinds of structures ranging from houses, barns, power line towers, churches and bridges to high-rise apartment and office buildings, adding visibility and reputation to the system (Sanders, 2011).

Figure 1. Schematic of CLT layer configuration.

CLT is not just a material, it is a building system composed of large format solid timber panels that can be used as walls or slabs (Lehmann et al., 2011). These panels were created initially as an extension of the technology that began with plywood and some have described it as “Jumbo Plywood” (FPInnovations, 2013; Podesto, 2011). The system is based on the use of massive laminated panels made from lumber boards that are glued together, alternating the direction of their fibers for each layer, which improves rigidity, stability, and mechanical properties Figure 1. Its distinctive structure implies that the element can take up forces in all directions (ANSI, 2012). Typically, a cross section of a CLT element has between three and seven (always odd numbers to achieve a balanced construction) glued layers of boards placed orthogonally to each other. The final dimensions of CLT panels are typically between 2 and 9 feet wide, and up to 79 feet long (Crespell et al., 2011). In special applications, unique configurations can be created, for example consecutive layers may be place in the same direction to obtain specific structural performance (FPInnovations, 2013). Also, lumber in the outer layers of CLT panels used as walls are normally oriented up and down, to maximize the wall’s vertical loading capacity. Likewise, for floor and roof systems, the outer layers run parallel to the major span direction (FPInnovations, 2013). During the manufacturing of the panels, lumber is visually graded or machine stress-rated and kiln dried before boards are finger jointed and glued together using structural adhesives. After panels have been pressed and machine-surfaced, openings for windows, door and service channels, connections and ducts are cut using CNC (Computer Numerical Controlled) routers, which allow for high-precision. Finally, elements are packed and sent to the construction site, ready to be put into place with cranes. CLT elements are connected to each other using simple metal connectors such as steel angles, and metal splines. Screws are used to attach these connectors to the panels (Crespell et al. 2011).

The European experience

CLT technology was developed in the early 1990 in Switzerland, as a cooperative project between industry and academic partners to find a practical uses for discarded wood (KLH, 2013; Podesto, 2011). As the market in Europe began demanding more environmentally friendly products, more people turned to CLT for their construction needs and CLT quickly grew in popularity over the past two decades, with now more than one hundred CLT projects completed in Europe (Lehmann et al., 2011; Sanders, 2011).

According to a report by Ebner (2010), the top European producers of CLT panel systems were operating at 120% of capacity in 2009–2010 and were projecting a 20% growth in production in 2010–2011, which highlights the success of the system on the European continent. The same study notes that total production volume of CLT panels reported for 2009 was 269,500 m^3. Production for 2012 (including new producers and new plants in the Czech Republic, Italy and Austria) exceed 520,000 m^3 (Ebner, 2010).

According to Lattke et al. (2007), construction with CLT panels in Europe has resulted in innovative projects, such as the Stadthaus in London, a renowned example. The developer that commissioned the design requested a building that looked and felt as if it was built in concrete, to avoid public acceptance issues (Lehmann et al., 2011). Designed by Waugh and Thistleton Architects, and built in 2008, the nine-story apartment building includes nineteen private apartments, ten social housing units and a residential housing office. The apartments are a mix of one, two and three bedroom units (Wells, 2012). Foundations and ground floors were built using concrete, while the remaining floors were built in CLT (Wells, 2012; KLH, 2013). Each floor of the building was assembled in three days using four workers, a task that would have taken more than forty-five weeks to be erected in concrete, took only twelve weeks in CLT (KLH, 2013). In regards to fire regulations, meeting Building Code requirements was relatively straightforward, relying on the self-protecting properties of timber which can retain its strength during fire for longer periods than steel (KLH, 2013; Kaufmann, 2012; Wells, 2012). Probably the most impressive feature of the Stadthaus building is that it is the first high-rise building (over 6 stories) using wood as its structural material.

The Australian experience

The Australian experience with CLT has not been as fast-paced as Europe's, mainly because of the fact that initially there were no manufacturing companies in the country and the product had to be imported from Europe (Australian Forest Products Association, 2014). This situation has been gradually changing as the Australian manufacturing industries started entering the market.

So far, only a few CLT buildings have been designed and built in Australia. The Forté Building is one of the most notable examples, being the first 10-story wooden building in the World. This multi-family residential building in Melbourne's Docklands is Australia's first large CLT building and a milestone project for the whole wood industry in the region (Lend Lease, 2013). It is so far the tallest wooden building in the world.

The intrinsic characteristics of CLT were particularly relevant to the Docklands location, since the reduced weight of the structure enabled substantial savings on the foundation construction. It took only twenty eight days to assemble seven hundred and sixty panels (around twenty five panels per day) of CLT, which were shipped from Austria (Hopkins, 2012). In regards to its environmental impact, according to the developers, by using CLT, Forté reduced the carbon emissions by more than 1,400 tons of CO_2 when compared with other building materials like concrete and steel. Moreover, the twenty three apartments require 25% less energy to heat and cool than a similar apartment built in concrete (Lend Lease, 2013; Hopkins, 2012).

The North American experience

Although this system is well established in Europe, the implementation of CLT has just begun in North America. Interest in the use of CLT in Canada and the U.S. has been increasing significantly in the last few years (FPInnovations, 2013).

In Canada, CLT is gradually becoming an accepted material in the construction of multi-story buildings (Canadian Wood Council, 2013). Four companies are offering the product in Canada. One of the first CLT structures was constructed for the 2010 Winter Olympics in Vancouver. Since then, it has been used successfully in hybrid structures (together with concrete slabs) such as the one in the Earth Sciences Building at the University of British Columbia and the Wayne Gretzky Centre in Ontario (Gauer, 2013).

The success after the recent introduction of CLT in the Canadian market indicates that there is a potential for further market penetration (Naturally Wood, 2013). The implementation of CLT in Canada has been promoted by FPInnovations (FPInnovations, 2011; FPInnovations, 2013). This organization published in 2011 the Canadian edition of the CLT Handbook, to assist design and provide construction information about CLT under the "Alternative Solutions" path in the Canadian Building Code (FPInnovations, 2013). Also the work carried out by WoodWorks (2013) and FPInnovations to promote the use of this system through reports, symposiums, webinars and construction fairs has greatly improved the visibility of the system throughout Canada.

However, CLT is still relatively unknown in the U.S. market. Currently, CLT is not produced commercially in the United States for structural purposes, but interest in the technology is growing and domestic production is expected by 2015 (FPInnovations 2013). Already two companies are working on establishing manufacturing capacity for CLT in the county.

At the moment, there are three CLT buildings in the U.S., all of which have been constructed with panels imported from Europe. The first North American non-residential CLT structure was the Myers Memorial United Methodist Church Bell Tower completed in 2010 in Gastonia, North Carolina. In the commercial sector, the first CLT building was concluded in 2011 in Montana. According to a report by WoodWorks (2012), the "Long Hall" is a mixed-used, urban infill design to replace a sixty year old construction in downtown Whitefish, Montana. Originally the design was created to be constructed in concrete but was then converted to CLT. The two-story wood structure took just five days to erect, and resulted in an "energy-efficient and environmentally friendly building" (WoodWorks, 2012). The third CLT building in the U.S. is the Crossroads building in Madison, Wisconsin. It combines the use of CLT with glulam beams to achieve larger spans while supporting heavily loaded areas (WoodWorks, 2012).

The introduction of CLT into the U.S. market is being supported by the American Wood Council's WoodWorks program (AWC, 2013) and The Engineered Wood Association (APA, 2013), which are leading the development of American National Standards Institute (ANSI) product standards for the national production of CLT (Evans, 2013; Georgia Forestry Commission, 2011; APA, 2013). Also, as a way to assist the U.S. architecture community and provide a similar path to CLT's code and standard inclusion as it was being pursued in Canada, FPInnovations and WoodWorks developed the 2013 U.S. edition of the CLT Handbook (FPInnovations 2013).

Economic and marketing studies conducted by FPInnovations (2011) seem to indicate that there is an opportunity for CLT as a building technology to meet the growing demand for mid-rise (four to six stories) buildings. It has been estimated that commercial and institutional buildings make up 87% of the non-residential opportunity for CLT (FPInnovations, 2013).These sectors are the ones with the largest increase in new wood construction with commercial buildings with an annual increase of 3%, office buildings a 9.1% annual increase, and lodging a 11.6% annual increase since 2009 (USDC, 2013; McGraw Hill Construction, 2012). According to the CLT Handbook, once realized, the expected U.S. CLT demand will be around $2 and $6 billion annually, most of which will be located on the East Coast (Boston and New York), the Great Lakes States (Minneapolis), California (Los Angeles), Washington (Seattle) and Texas (Dallas and Houston).

CLT has been presented as an environmentally superior and cost-competitive alternative to concrete or steel, the price of which continues to rise at higher rates than softwood lumber. The percentage change in Producer Price Index (PPI) for precast concrete has increased 44.8% since December 2003, while the same index for lumber and plywood has only increased 7.2% in the same period (APA, 2008; AGC of America 2013). Cost simulations for CLT established that the cost of production and construction for CLT is approximately $14/square foot compared to $22/square foot for a 7-inch post-tensioned concrete slab and frame (FPInnovations, 2013; McGraw-Hill Companies 2013). These estimates account only for the cost of the panels but do not include the labor and time savings from using CLT.

Benefits of CLT

Environmental performance and sustainability

In addition to humanity's historical connections to wood as a construction material, wood offers multiple benefits, especially in regards to environmental performance. When forests are sustainably managed, wood is carbon-neutral, and acts as a repository of carbon, either as growing stock or as a value-added product (Bowyer et al., 2011). Trees convert carbon dioxide to biomass in the process of carbon sequestration using photosynthesis (Lehmann et al., 2011). One cubic meter of wood stores around 1.10 tonnes of CO_2 per cubic meter (Malmsheimer et al., 2008)for the time that these products are in use, usually decades (Troldtekt, 2013). Research conducted by Lippke (2011) on sustainable forest management and the lifecycle of wood products in construction, shows that instead of keeping wood growing in forests for hundreds of years, it is beneficial for the forest to be regularly harvested to remove diseased, burned, or insect infested trees and promoting the healthy regeneration of new trees (Ritter, 2011; Lippke et al., 2011; Idaho Forest Products Commission, 2013).

In comparison, steel and concrete, while being high-performing and versatile building materials, show a very different performance in regards to their environmental footprint: for example, five percent of all Green House Gas (GHG) emissions worldwide are caused by concrete manufacturing and use. In this sense, wood in general and CLT in particular outperforms both concrete and steel (Wilson et al. 2005; Lehmann et al. 2011). Life Cycle Analysis (LCA) research on wood products has demonstrated that wood produces less greenhouse gases, and requires smaller amounts of water, energy, and fossil fuels to transform than concrete and steel (Puettmann et al., 2010; Bergman et al., 2010; Oneil et al., 2010; CORRIM, 2006).

Installation simplicity and cost competitiveness

One of the most attractive features of CLT as a building system relates to the speed in which CLT buildings can be erected (Ceccotti et al., 2010). The prefabricated nature of CLT allows for high precision and a construction process characterized by faster completion, increased safety, less demand for skilled workers on site, less disruption to the surroundings, and less waste generation (Evans, 2013; FPInnovations, 2011; APA, 2013).

CLT elements can be used for roofs, walls and flooring structures, and they can be delivered from the factory in various sizes and shapes (which are usually limited by transportation requirements). Openings for windows and doors can be cut with precision using CNC machines (Evans, 2013; Crespell et al., 2011). This computerized system improves the efficiency in the use of wood resources, minimizing manufacturing waste and time, and guaranteeing the precision of the final product.

On site, the CLT structure is assembled using very simple mechanical fastening systems, which enables the creation of a structurally stable construction with excellent response to vertical and horizontal forces. CLT elements only require simple tools and screws as well as on-site cranes for lifting and mounting the elements (Kirkegaard 2012; Evans, 2013).

Several case studies by WoodWorks (2013) highlight the rapid on-site construction that may be as short as three to four days per story. Such short construction times, compared to traditional construction methods, allows faster completion of the projects and therefore less labor costs associated (Waugh, 2011; Pons, 2012).

Structural performance

One of the most impressive advantages of CLT elements is their strength to weight ratio compared to other materials. For example, Bogensperger et al. (n.d) established that mechanical properties of CLT compressed orthogonally to their fiber direction are significantly better than those of comparable Glulam elements. The reason for this can be found in the cross-laminated configuration of CLT. Whereas glulam features only unidirectional layers, CLT elements are built with layers orthogonal to each other. In this way, adjacent layers of CLT elements support each other and act as reinforcement, which leads to better mechanical properties. Also due to this distinctive structure, each CLT element constitutes a stable structure by itself that is able to resist forces in all directions (Pons, 2012). Those characteristics allow CLT panels to be used for walls, roofs, and floors. Thus, CLT can be used as load-bearing elements and even shear panels; something that distinguishes CLT from other wood-based panels (Steiger et al., 2008). This way, CLT allows a new way of building structures, and shifts the design from “frame” to “plates” (Kirkegaard, 2012).

Some variations of the typical massive panel have also been developed, such as “cassette” floors, where two cross-laminated timber plates are connected with wooden ribs to form the hollow core elements, allowing even greater spans. The idea behind this is to reduce the slab’s weight without compromising its strength (Crespell et al., 2010;

Chen, 2011). Another variation is the “interlocked” panel which, unlike traditional CLT panels, does not use adhesives during its manufacturing but tongue and groove and dovetail joinery to “lock” each board and layer. This removes the use of volatile organic compound (VOC)-emitting adhesives, allowing the panel to be disassembled at end of life and be reused (Smith, 2011).

Design flexibility

The structural characteristics of CLT allow for shapes and openings of the most diverse sizes and forms, without compromising the structural integrity of the structure (Santos, 2008; Kirkegaard, 2012; FPInnovations, 2013; WoodWorks, n.d., Evans, 2013). Due to the fact that the size of the elements is virtually limited only to manufacturing and transportation capacity gives the designers the possibility to have fewer but larger elements to create the same stable construction that could be achieved with more traditional materials. A construction with fewer elements implies also greater simplicity. More complex designs can be achieved (form, height, spans, among others) without the actual construction becoming more complicated. The fact that the building is simplified to a few basic elements, allows for greater freedom for the construction professional (Waugh, 2011).

Fire and seismic performance

The main goals in establishing the fire resistance of a structure are first, to provide a safe evacuation time for occupants, preventing fire and smoke to spread, and second, to guarantee structural integrity while firefighters work (Phan, 2010). Usually people wrongly assume that wood buildings perform poorly in fires, since wood is a combustible material. However, wood members with large cross-sections have the inherent ability to provide fire resistance because of wood’s unique charring properties (Stone et al., 2013; FP Innovations 2011). They burn more slowly and predictably, and form a char layer that protects non-charred wood, allowing it to maintain its strength and dimensional stability without abruptly collapsing, like steel does (Forest Products Laboratory, 2010, Frangi et al., 2009).

In terms of fire protection, the International Building Code (IBC, 2012; Fracis, 2013) requires all buildings to perform to the same level no matter the material. Results of full-scale fire tests, conducted in accordance with ASTM E119 standard (ASTM, 2012) test method in the Forest Products Lab (Dagenais et al., 2012) show that CLT has the potential to provide excellent fire resistance, often comparable with typical non-combustible materials. Because they char at a slow and predictable rate, CLT panels can maintain structural capacity for an extended period of time when exposed to fire (Stone et al., 2013; Frangi et al., 2009; and FPInnovations, 2013). These studies have also shown that adding one or two layers of gypsum could provide an additional thirty and sixty minutes of fire resistance, respectively. According to Frangi et al. (2009), CLT's fire performance does not only depend on wood but also the adhesive used to bond boards and layers together, thus using adhesives with lower sensitivity to high temperatures will greatly improve the fire behavior of CLT panels. The tight nature of CLT buildings also improves fire performance by limiting the spread of fire to adjacent spaces (Craft, 2011).

In terms of seismic performance, wood buildings perform well because they are lighter and more ductile than structures built with traditional materials (Popovski et al., 2010). To confirm this, the Trees and Timber Research Institute of Italy tested a full scale seven story CLT building on the world's largest shake table in Japan, with excellent results. Even when subjected to a severe earthquake simulation (magnitude of 7.2 in the Richter scale), the structure showed no significant deformation after the test (Popovski et al., 2010).

To develop a practical seismic design procedure for CLT buildings, a number of walls with different geometry and connector configurations were tested in Canada by FPInnovations (Pei et al., 2012). Results from these tests on single CLT wall panels showed that the connection layout and design has a strong influence on the overall behavior of the wall (Pei et al., 2012; Ceccotti et al., 2006) and the resulting system can be very resistant and ductile. It was shown that CLT walls allow movement of the wall panels, which is an essential condition for structures to resist seismic forces (Lauriola et al., 2006).

Thermal performance

Air tightness of a building is critical for its performance (Burnett et al., 2005), because this property determines the insulating performance of the wall, thus controlling the indoor climate. The U.S. national building regulations include rigorous requirements for air leakage through the building envelope, in order to reduce the energy consumption, not only during winter in cold climates like Minnesota, due to heating loads (Skogstad et al., n.d.), but also during summer, due to cooling loads. Regarding this matter, the main advantage of CLT is that it offers the possibility of creating a tight construction, due to the large panels and the possibility of having fewer elements and thus fewer joints where air could infiltrate to the building (Skogstad et al,. n.d.).

According to Burnett et al. (2005), studies have shown that CLT offers a good amount of thermal inertia. CLT panels both in the building enclosure and in interior floors and walls acts as a thermal mass that stores heat during the day and releases it at night. Thermal mass can greatly reduce (for some climates and for sometimes of the year) heating and cooling loads, shift the time of peak loads, lower overall building energy use and enhance occupant comfort (Burnett et al., 2005; Straube, 2012; Lstiburek, 2012). The insulating capacity of these massive walls may reduce the need for insulation (Falk 2005).

Barriers to CLT implementation in the U.S.

CLT has been very successful in Europe (Evans, 2013), and is attracting considerable attention in North America as an engineered wood product that can be used as an environmentally friendly alternative to concrete or steel. However, there is still a gap in knowledge about existing barriers that needs to be addressed (Schmidt et al., n.d,).

Usually fire requirements, decay potential and insect problems are named as the reasons for some people's unfavorable views about wood-based construction in general, and of CLT in particular. Generally, wood is seen as a risky option compared to concrete, steel or masonry. It is a common belief in places with less wood tradition that this material is not able to withstand time and that its lack of durability implies high maintenance costs

(Lehmann et al., 2011). Social acceptance plays a vital role in the implementation of any new technology and therefore constitutes an important potential barrier to the adoption of CLT (McKenzie-Mohr, 1995; Yuan et al., 2011).

Technological barriers can also be encountered. Due to the fact that this is a solid wooden panel, systems that usually hide inside a wall frame (plumbing, electrical, etc.), now require more attention for its integration with the structural system. This means more careful planning for pipes, electrical wiring openings, and other components that might need to pass through the panels (Griffin, n.d.).

Compatibility with the existing building code has also been identified as a barrier to the implementation of the CLT building system in the U.S. Although several structures have been built using CLT panels in North America, these constructions are generally designed and built under an engineer's approval and vetted by the governmental entity on a case-by-case basis (FPInnovations, 2011; Schmidt et al., n.d). The existence of a standard that regulates the design of CLT element would certainly be a step forward to a successful acceptance of CLT in the U.S.

In Europe, building codes under which CLT construction has been regulated (Eurocode 5: EN 1995) have been in use for 19 years (TRADA, 2013). The United Kingdom, Norway and New Zealand place no height restrictions on safely-made wooden high-rise buildings (Lehmann et al. 2011). In North America, Canada recently changed its building codes to allow taller buildings to be made from wood. However structures in Canada are still limited to six stories (Structurlam, 2013).

In the U.S., neither the International Building Code (IBC, 2014) nor the National Design Specification for Wood Construction (AWC, 2014) published by the American Wood Council, have yet included CLT in their scope. The lack of a code that regulates the use of CLT in the U.S. strongly obstructs the adoption of CLT. According to FPInnovations (2013), a proposed CLT code should take into account the capabilities of the system and allow the utilization to its full potential, not limiting, for example, the height of CLT buildings to 5-6 stories.

Efforts towards removing code barriers and regulate CLT construction in the U.S. have been carried out with support from FPInnovations and The Engineered Wood Association (APA, 2013), by establishing a U.S.-Canada CLT Standard Committee. In parallel, the American National Standards Institute (ANSI) approved the ANSI/APA PRG 320-2011 Standard (Standard for Performance Rated Cross Laminated Timber) in December 2011 (ANSI, 2012). ANSI/APA PRG 320 provides standards and test methods for qualification, quality (wood, adhesives, and dimensional tolerances), resistance (bending, modulus of elasticity, shear and bonding) and appearance (architectural and industrial) assurance for CLT. It should be noted that ANSI/APA PRG 320 is not a CLT design standard and does not address design specific issues, such as creep, duration of load, volume effect, lateral load resistance, connections, fire, energy, sound, or floor vibration (ANSI, 2012; FPInnovations 2013). However it marks an initial step towards the regulation of the manufacture of CLT panels in the U.S.

The International Standards Organization (ISO) Technical Committee 165 on Timber Structures has also initiated a project to develop an ISO standard for CLT under the leadership of the Forest Products Laboratory of the U.S. Department of Agriculture (Forest Products Laboratory, 2013). This standard is intended to combine the CLT standards from North America and Europe as one international standard, regulating CLT construction around the world (FPInnovations, 2013). Lastly, the National Design Specification for Wood Construction is expected to include a section specifically on CLT (AWC, 2012).

Project description

From the literature review, it was found that there is an abundance of information on the technology of building with CLT. However, one area that has received limited attention has been the market potential for CLT in the U.S., including the level of awareness among the public and specifiers of construction materials, perceptions about CLT, and the willingness of these actors to adopt CLT. This study addresses these topics, important in the adoption of any new product or technology. Although several actors participate in the decision to select a specific material for a building project (i.e., engineers, developer, architects, final user), this effort focuses on the role of the architect.

Objectives

The purpose of this study was to assess the market potential for Cross-Laminated Timber (CLT) in the United States. To accomplish this goal, the following specific objectives were proposed: (a) learn about the perspectives of experts about the awareness, perceptions, and willingness to adopt CLT by the U.S. architecture community; (b) estimate the level of awareness about CLT among architectural firms, learn the perceptions about the environmental, structural and economic performance of CLT, and assess the willingness to adopt CLT by the U.S. architecture community; and (c) explore the architectural possibilities of CLT, through the design of a multi-family residential building.

Results from this research benefit entrepreneurs with interest in entering the CLT market (as suppliers, designers, or manufacturers), by providing them with important information about architects' perceptions about CLT and their willingness to adopt it as a building material. Outcomes also inform organizations supporting the forest products industry, such as government and industry associations. CLT is an opportunity to produce a high value-added product from underutilized forest resources, and generate employment in rural communities, where a disproportionate number of forest products jobs are found.

Summary of the research approach

To achieve the objectives of this research, the project was carried out in three stages: (1) interviews with CLT experts; (2) survey of the U.S. architecture community; and (3) exploration of the architectural possibilities of Cross-Laminated Timber. In this document, each research stage will be presented in an individual chapter. Figure 2 illustrates the research approach used in this study.

Figure 2. Research methodology.

Interviews with CLT experts

A set of semi-structured phone interviews was conducted with experts to obtain specific information and insights on several topics. Interviews were conducted over the phone or via Skype and were recorded (with the participant's consent) for analysis and future reference (see Appendix 1). A list of ten questions was prepared. Questions covered the following categories: demographic information; benefits and barriers for the implementation of CLT in the U.S.; awareness of CLT in the architecture community; perceptions about CLT and willingness to adopt CLT.

Once the interviews were concluded, recordings were transcribed, coded and analyzed. Results from these interviews were then used to formulate a set of questions to be included in the next part of the study: a nation-wide survey of architecture firms. A more complete description of the methodology and results obtained from this part of the study are presented in Chapter 2.

Nationwide survey of the U.S. architecture community

The third part of the study consisted of a nation-wide internet-based survey of architecture firms, specifically firms specializing in commercial building construction. This survey population is comprised of some of the most important specifiers of materials used in the construction industry, a critical group for the adoption of CLT.

A sample size of 1,627 surveys was calculated (detailed calculation in Chapter 3). The mailing list of names and contact information was compiled randomly using the American Institute of Architects (AIA) online database (AIA, 2014).

Based on the information obtained during the preliminary interviews, an eleven-item questionnaire was drafter. The following topics were included:

- Demographic information: location and size of the firm.
- Awareness of CLT in the architecture community: familiarity with CLT, how participants learned about the system.
- Perceptions towards CLT: how participants perceive the environmental, structural and economic benefits of the system.
- Willingness to adopt the CLT building system.

Once the questionnaire was created, a draft was sent to eight experts to obtain their feedback regarding clarity and consistency of the questions, potential errors, and suggestions for improvement. The survey was conducted with an online resource: (Qualtrics, 2014). First, a personalized email with information about the purpose of the survey and a request for participation was emailed to the potential participants, along with the questionnaire. The first reminder was sent a week after the first email was sent to request a response from those who did not replied. Three weeks after the first questionnaire went out, a second reminder was sent. The survey concluded January 15th, 2014, five weeks after the first distribution.

Data obtained from the survey was analyzed using standard statistical techniques, such as descriptive statistics and charts. Categorical data was evaluated using chi-squared test. All statistical tests were evaluated at a 0.05 alpha level. The complete methodology followed and results obtained from this study are presented in Chapter 3.

Architectural exploration

One important information that was obtained from the market analysis are the types of building construction (e.g., residential – single-family or multi-family housing, non-residential – commercial, educational, governmental) perceived as the ones with the highest potential to use CLT as main material. These results represented a major input for the third phase of the project.

In the last part of the research project, preliminary design of a CLT-based building was carried out. An architectural design project is an excellent opportunity to apply concepts and technical information to a real situation, while providing additional information for the theoretical discussion. Within the various variables that the project could consider, only those relevant from the architecture's perspective were applied. Technical features of the system were considered more as an exploration of possibilities rather than as design constraints. Insights from CLT manufacturers that worked with CLT in the past were requested. A set of blueprints, including floor plans, elevations, sections and construction details of particular elements were developed using AutoCad software (Autodesk, 2014). Additionally, 3D renderings were created to illustrate the spatial possibilities of CLT. For this purpose, Archicad (Graphisoft, 2014) and Adobe Photoshop (Photoshop, 2014) were used. Detailed outcomes from the architectural exploration are presented in Chapter 4.

Chapter 2

Interviews with CLT experts

Introduction

This chapter presents the results obtained from a series of interviews to CLT experts. The goal of this part of the study was to assess the market potential of Cross-Laminated Timber (CLT) and to identify the potential barriers to adoption in the United States. For this purpose, the perspectives of experts about the awareness, perceptions, and willingness to adopt CLT by the U.S. architecture community were collected. Semi-structured interviews allow gathering in-depth insights on several topics from a very specific targeted sample (Babbie, 2007). The methodology, results, and conclusions are presented in the following sections.

Methodology

Interviewee recruitment

A list of ten CLT experts was compiled, based on their experience and knowledge of the topic. The majority of these contacts were found in the relevant literature, while the rest was derived from recommendations by academic experts. The list of experts included professionals from the academic, manufacturing, architecture, and industry promotion communities. Participants were located in the U.S., Canada, and Austria.

Interviewees had diverse backgrounds and experience related to Cross-Laminated Timber (CLT). One of the interviewees reported being the first to conduct market analysis on CLT in the U.S. Two participants contributed as co-authors to the creation of the first U.S. edition of the CLT Handbook (FPInnovations, 2013). One expert indicated having experience in manufacturing, construction, and cost estimation of CLT structures, as well as having conducted competitiveness analysis and cost comparisons between CLT and concrete, steel, and traditional light-frame construction. Another interviewee has been conducting research on the North American production potential for CLT. The representative of an organization that promotes the use of wood in commercial buildings reported having more than eight years of experience conducting workshops, seminars, webinars, and various technical assistance efforts for CLT aimed at the architecture, engineering, construction (AEC) community. Two of the interviewees were involved in the experimental modeling of CLT for seismic performance. One manufacturer representative indicated that previously to establishing a CLT plant in North America, he worked as cost controller and project manager in the United Kingdom. Two other participants from industry have been pursuing research on wood and related subjects for years, which led them to work for CLT manufacturing companies as Technical Assistants.

Questionnaire design

A semi-structured questionnaire was used to obtain information and insights on topics relevant to existing and potential markets for CLT in the U.S. Participants were contacted via email and phone to arrange a convenient date and time for the interviews. Interviews were conducted via phone in the summer of 2013. A questionnaire with 15 open-ended questions was developed. Questions were based on the preliminary information obtained from the literature review. The questionnaire asked for information and perspectives on the following topics:

- Demographic and background information: interviewees' knowledge and experience with CLT.
- Environmental, structural, and economic performance of CLT.
- Barriers to adoption of CLT in the U.S.
- Awareness of CLT in the U.S. among the architecture, engineering and construction (AEC) community.
- Cost-competitiveness of CLT compared to other construction systems.
- Types of buildings where CLT has the highest potential for adoption.
- Other comments regarding the potential for adoption of CLT in the U.S.

Data analysis

The duration of each interview was between 10 to 35 minutes. The interviews were audio-recorded with the consent of the participants and notes were taken as a backup.

Each interview recording was fully transcribed. Transcriptions were coded according to the topics mentioned by participants. Established qualitative research methods for thematic content analysis using the constant comparative method (Glaser and Strauss, 1967; Berg, 2001; Robson, 2002) were used to analyze and to identify major themes from the transcripts. Organization of the responses and analysis were carried out using Excel spreadsheet software (Microsoft, 2010). A total of 10 topics and 88 subtopics were identified.

Limitations

A number of limitations may have affected the results obtained from this part of the study. Limitations include:

- Due to the small sample size, generalization of results is not feasible. This part of the research was exploratory in nature and was focused on depth of information and not statistical representation.
- Participants working in the manufacturing sector as well as in the promotion of wood products may tend to have a positive bias for wood-based construction materials.
- Some professionals, such as engineers, contractors and developers, who may have relevant knowledge and insights, are not represented in the sample.
- Interviewees may not have given accurate and/or complete answers (Oatey, 1999).
- The absence of visual cues via telephone results in loss of contextual and nonverbal data, therefore compromising quality of responses (Opdenakker, 2006).
- Telephone interviews usually need to be kept short, thus reducing in-depth discussion (Chapple, 1999; Creswell, 1998; Sweet, 2002).

A detailed discussion of the findings, organized by topics, is presented in the following sections. Topics included are the environmental, structural, and economic characteristics of CLT, CLT's limitations and barriers, and potential applications in the U.S.

Results and Discussion

Environmental characteristics of CLT

The environmental benefits of Cross-Laminated Timber (CLT) have been widely documented (Schlamadinger et al., 1996; Winjum et al., 1998; Salazar et al., 2009). Eight respondents agreed that the carbon sequestration achieved by the use of CLT is one of its most important environmental benefits, and that this provides a unique opportunity to market the product (selling point) to environmental-conscious consumers in the U.S. (Qi et al., 2010; Wang et al., 2013). In fact, the carbon-storage capacity of wood products is gaining recognition in domestic climate mitigation programs such as the ones promoted by the Environmental Protection Agency (EPA, 2013; Malmsheimer et al., 2008) and the U.S. Forest Service (USDA, 2011). Wood products store carbon at an approximate rate of 1.10 tonnes of CO_2 per cubic meter for the time that these products are in use, usually decades (Malmsheimer et al., 2008; Troldtekt, 2013).

Interviewees also emphasized the lower greenhouse gas emissions and the lower energy input required for the manufacture of CLT panels, especially compared to the more polluting, energy-consuming processes to produce equivalent elements from concrete or steel. Research using Comparative Life Cycle Analysis (LCA) of building materials, i.e., the evaluation of environmental impacts during raw material extraction, transportation, and processing, confirms the participants' assertions (Puettmann et al., 2010; Bergman et al., 2010; Oneil et al., 2010; CORRIM, 2006; Silvestre et al., 2013; Wang et al., 2013). According to Malmsheiner et al. (2008), substitution of building elements that require intensive use of fossil fuels for their production (e.g., steel- or concrete-based elements) with wood-based products allows achieving considerable reductions in carbon emissions to the atmosphere, making CLT construction systems an environmentally-friendly alternative to more energy-intensive materials. One respondent mentioned that LCA of existing CLT buildings showed that these buildings have a negative carbon footprint. Research conducted by Hammond et al. (2011) in the United Kingdom showed that concrete and steel solutions contain around the same amounts of embodied CO_2 (1,984 tonnes) while an equivalent CLT system has less than a half that amount (727 tons). However if carbon sequestration is taken into account, CLT turns out to be carbon-negative, with a value of approximately -2,314 tons of embodied CO_2 per cubic foot, making CLT far more environmentally-friendly than other types of structures (Hammond et al., 2011).

The two manufacturer representatives in our sample stated that the biggest environmental benefit of CLT stems from the potential for using underutilized forest resources to manufacture CLT panels. Similarly to other engineered wood products, the structural performance of CLT panels does not depend on the mechanical performance of each individual component of the composite but on the overall system; hence CLT presents the opportunity for using lower quality and underutilized material for its production. Similarly, raw materials from forests damaged by insect or disease could possibly find a high value-added use, as long as the mechanical properties of these materials are not compromised (Wilson, 2012). This way, multiple benefits can be derived from using low-value raw material for a high-value use and wood products that continue to benefit the environment long after timber is harvested through carbon sequestration (Salazar et al., 2009; Wang et al., 2013). This would also help forest managers to manage the forest more proactively and profitably while reducing existing fire hazards. According to one of the Canadian industry representatives, their company uses considerable amounts of raw material coming from beetle-infested pine trees from the Pacific Northwest forest, thereby allowing a more effective and efficient use of natural resources, as otherwise this material may be wasted.

Mardookhy et al. (2013) indicate that according to data from the U.S. Energy Information Administration (EIA), more than 48% of the total building energy consumption corresponds to the use of room heating and cooling equipment. Consequently, improvements in the building envelope can help reduce environmental polluting emission such as carbon dioxide originated from energy generation (Reijnders et al., 1999; Mardookhy et al., 2013).The CLT experts interviewed noted the favorable properties of wood in respect to heat transfer and storage, especially compared to some of the possible alternative materials (e.g., steel, concrete (Loghmanpour, 1996)). Experts mentioned that not only does wood have favorable thermal insulation properties, but as CLT makes massive use of wood for the building enclosure and the interior floors and walls, it acts as a thermal mass that stores heat during the day and releases it at night. This thermal mass can reduce heating and cooling loads, shift the time of peak loads, lower overall building energy use, and improve occupants overall comfort (Burnett et al., 2005). According to one of the interviewees, the insulating capacity of CLT also helps in reducing the amount of insulation material needed to achieve a low operational energy consumption of the structure (Reijnders et al., 1999

A recent report performed for the Forte Building in Melbourne, Australia under the ISO 14040 standard (Durlinger et al., 2013) helps exemplify all the above mentioned environmental characteristics of CLT. The study compared the environmental impacts of both the Forte Building (first 10-story CLT building in the World) and a reference concrete building. Results show that even though the CLT panels for the Forte building were imported from Europe and the reference building's materials were domestically produced, the Forte building still had a lower impact for materials and transport when compared to the reference building. If carbon sequestration is included in the analysis, the Forte building's impacts were calculated to be 22% lower on global warming potential, while if sequestration is not included the estimated impacts were 13% lower. Also, cumulative energy demand was calculated to be 16% lower, which speaks of the insulation capabilities of the CLT system compared to concrete.

A similar study performed at the University of British Columbia (Robertson, 2011) compared the environmental performance of CLT and concrete-based building design alternatives on 11 impact categories. The results show that the CLT building design was associated with a lower environmental footprint in 10 of the 11 categories in consideration. Compared to the concrete-based building, the CLT building demonstrated a 14% improvement of the overall footprint, and a global warming potential that was 71% less than the concrete-based design, which reinforces the perceived environmental advantages of CLT compared to more traditional materials.

Similar results have been obtained from the Life Cycle Analysis of other EWPs. An example of this is presented in the report published by Consortium for Research on Renewable Industrial Materials (CORRIM), a research project to "develop a scientific base of information relating to the environmental performance of wood based building products" (Puettmann et al., 2005). The results published in this report are consistent with previous studies conducted in Europe (Buchanan, 1993; Richter et al., 1993) which show that the manufacturing of EWPs is significantly less energy demanding than the manufacturing of alternatives such as concrete or steel. From all the life cycle stages that are taken into account for the analysis, the harvesting and transportation stages produce fewer emissions, while operations such a wood drying and adhesive manufacturing are much more energy-intensive and therefore have a higher impact on the environment.

Structural characteristics of CLT

Some of the structural advantages of CLT mentioned by the interviewees in this study are derived from the physical and mechanical properties of wood, which have made this material so popular for building construction throughout history. Six interviewees agreed that one of the most important characteristics of CLT was its weight-to-strength ratio. One participant mentioned that *"... [*CLT is*] as strong and [*performs*] as well as concrete but it weighs one-sixth of concrete."* When loaded, wood can have a weight-to-strength ratio advantage relative to steel of 2:1 and an even more favorable ratio if compared to concrete (Architectural Record, 2011). An important benefit of using a material with low weight-to-strength ratio like CLT is that lighter structures with comparable structural capabilities can be achieved. Furthermore, a lighter structure translates into smaller building foundations, which in turn translates into lower building costs. One manufacturer representative participating in the study explained that having less gravity loads makes CLT a far superior material over all the other competing materials.

The majority of the individuals interviewed indicated that the structural characteristics of CLT make it a preferred alternative to concrete structures, especially in high-rise constructions (over 6 stories). There are several successful examples worldwide of CLT used in tall buildings, prominent examples being the Stadthaus (an 8-story residential building in London, UK (KLH, 2013), and the Forte Building, (a 10-story residential building in Melbourne, Australia (Lend Lease, 2013). A recent report by the architecture and engineering firm Skidmore, Owings and Merrill (SOM) proposed a 42-story CLT-concrete hybrid building in Chicago, called Timber Tower Research Project (SOM, 2013). One of the respondents mentioned that his expectation is to see CLT enabling wood buildings to reach "*new heights*." Another respondent (an engineer) voiced some skepticism on this matter, saying that he is unconvinced about the ultimate number of stories that can be built with a CLT structure. When asked to elaborate on this skepticism, the interviewee indicated that there is a lack of models to predict the performance of high-rise wooden structures and mentioned that the highest building they have modeled in the laboratory is 15 stories high. The same expert stated that further research needs to be carried out, and improved solutions need to be generated before wood-based buildings can go beyond 20 stories; and that emphasis of those efforts should be on the connecting elements that hold the structure together.

Design characteristics of CLT

Two participants involved in research and one participant representing the architectural sector mentioned that another important structural benefit of CLT was its design flexibility. CLT lets designers have a plate element that can withstand forces in all directions, thus allowing curved, inclined, or folded geometries without compromising the structural integrity of the structure.

According to one of the respondents, CLT's ability to span in three directions allows the realization of architectural features that otherwise would be too complex or impossible to attain using wood in traditional ways. Furthermore, since the size of the structural elements is limited only by transportation constraints, designers are able to use larger and fewer plates to create a stable construction, which translates into a more simple, less error-prone construction, with less need of specialized labor and faster completion times (FPInnovations, 2013).

Fire performance of CLT

Some of the respondents also stressed the fire performance of CLT elements. While people often mistakenly assume that wood buildings behave poorly in fires (wood is a combustible material, and has been used as firewood since prehistoric times), research has shown that CLT elements perform exceptionally well (Fragiacomo et al., 2013; Schmid, 2010). In fact, large-sized wood members have shown an inherent ability to provide fire resistance because of their unique charring properties (Stone et al., 2013; FPInnovations, 2011). Respondents mentioned that CLT panels burn slowly and predictably, and form a char-layer and the non-charred internal wood layers retain their strength and dimensional stability, thereby delaying the collapse of structural members. Respondents indicated that in some respects, CLT performs better than, steel on structural and other dimensions. One interviewee mentioned that his research showed that CLT panels, due to their "*massiveness*" and "*tightness*," provide an extremely favorable barrier for gases and high temperatures during a fire situation.

Seismic performance of CLT

Researchers with a background in engineering interviewed for this study viewed the seismic performance of CLT as another major structural advantage of the material. Recent research (Popovski et al., 2010; Pei et al., 2012) found that the massive yet ductile properties of CLT are advantageous when subjected to lateral forces. Results from these tests on single CLT wall panels showed that, as discussed earlier, the connection layout and design has a strong influence on the overall behavior of the wall, but the panel itself performs favorably (Ceccotti et al., 2006).

Economic characteristics of CLT

Nine out of ten respondents recognized the speed of construction as one of the main cost advantages of building with CLT. In fact, the prefabricated nature of CLT allows bringing building elements to the construction site ready to install, shortening building completion time and requiring less qualified personnel (FPInnovations, 2013). One respondent stated that CLT elements *"…can be installed in one-third of the time compared to other products*." Respondents also mentioned that faster construction means fewer chances for on-site accidents and less disruption of the surrounding community, with positive consequences for the total costs associated with the construction (e.g., insurance, safety, goodwill). Two respondents mentioned that the speed of construction was particularly attractive to developers, who can realize the return on their investments more quickly: *"…[*CLT*] can go up so quickly that the people who are paying the bills for the projects can start making money from their investment much sooner"* and *"…so you save time, and get to move into that building sooner and the savings from that alone are quite substantial.*" WoodWorks (2013) highlight the rapid on-site construction that may take as little as three to four months for buildings of up to nine stories (Lehmann et al., 2011), less than half the time compared to traditional construction methods.

It has been proposed that CLT panels also promote more effective and efficient manufacturing processes as their final dimensions and openings are precision-cut using computer numerical control (CNC) machines at the factory (FPInnovations, 2013), thus contributing to the efficient use of wood and manufacturing resources. The controlled manufacturing environment also helps to reduce waste, cut total production time and facilitates the final installation thanks to high precision work, which potentially reduces the occurrence and costs derived from problems during construction and post-construction, thereby reducing costs considerably.

Three of the respondents working in manufacturing pointed out that using CLT is an opportunity to use local resources. One research about using hardwood species for CLT manufacturing in Italy (CLT is typically made with softwood species) concluded that the manufacture of these panels contributes to the valorization of locally available wood resources and to the development of the local wood-based industry (Callegari et al., 2010).

Disadvantages of CLT

Interestingly, the large volume of wood required to manufacture CLT panels, which was credited for some of its advantages (fire performance, thermal insulation, carbon sequestration capability) by our interviewees, was also cited as one of CLT's main drawbacks. One respondent with experience in design and calculation of CLT structures estimated that CLT panels use three times more wood than a wood-frame system solution. Consequently, participants indicated that this need for a larger volume of material also implies a higher cost, which can cause CLT-based solutions to be not cost-competitive for some applications. The large volume of wood used in the manufacture of CLT also may affect public perception about the system, as one respondent pointed out: "*…People will say that perhaps it is a lot of fiber engaged in CLT,"* while another respondent added that the depletion of our forests "… *Is a misconception because countries such as ours [Canada], with good forest management practices, do not have deforestation concerns."* The same can be said for the U.S., where four forest certification systems (standards that help to ensure the sustainable use of forest resources) are being used (Espinoza et al., 2012).

Another disadvantage mentioned by some of the respondents was related to the acoustic performance of CLT systems. One researcher mentioned that usually acoustic problems occur due to shortcomings in the installation and the lack of proper linings. Recent research found that thanks to its massive nature, CLT-based systems allow achieving good acoustic performance and providing adequate noise control for both airborne and impact sound transmissions, especially if sealant and other types of membranes are used to provide air tightness and improve sound insulation at the interfaces between the floor and wall plates (Gagnon, 2011). Figure 3 shows the floor assembly used for tests performed at the Technical Center of Forest, Wood Products and Furniture in 2006 (FPInnovations, 2013) showing that CLT floors built with proper insulation can achieve and exceed preferred (50 dB) and targeted (55dB) sound insulation thresholds (FCBA, 2006).

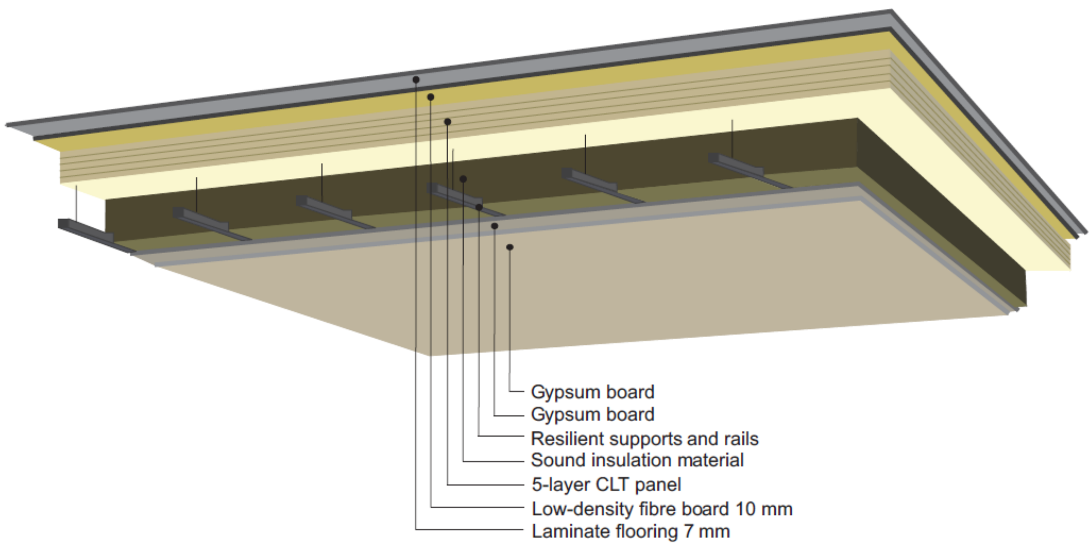


Figure 3. Cross-section of a tested CLT floor assembly. Based on CLT Handbook 2013 (FPInnovations, 2013).

An architect interviewed for this study mentioned that some technological barriers exist due to the solid nature of the CLT system, requiring professionals to change the way they design buildings. This respondent's assertion is supported by findings by Griffin (2013), who states that systems that usually are hidden inside a wall frame (e.g. plumbing, electrical), now need extra attention in their integration with the structure, which could imply more planning and manufacturing costs.

Another perceived disadvantage of CLT mentioned during the interviews is the fact that a sizeable percentage of people still do not completely trust the qualities of wood as a building material. Generally, wood is seen as a risky option compared to concrete, steel, or masonry. Individuals may believe that wood is not able to withstand time and that its lack of durability implies high maintenance costs (Lehmann et al., 2011). One of the researchers interviewed indicated that his main concern about the structural performance of CLT is the durability of the material, especially since wood is susceptible to moisture-related problems. These comments seem to suggest a need to develop systems to remove and replace CLT panels in need of repair or replacement without affecting the integrity of the rest of the structure.

Awareness of CLT in the architecture community

When respondents were asked about the level of awareness of Cross-Laminated Timber (CLT) in the architecture community, about half indicated it to be currently low or very low. Several of the respondents justified their response by saying that this low level of awareness is due to the short time this material has been available in the U.S. market. In particular, two researchers agreed that professionals not familiar with the wood industry are less likely to have heard about CLT. One researcher stated that *"... Because the marketing for this product is coming from the wood industry, people not connected with the wood industry are not aware of the product*." A second group of respondents indicated that the level of awareness of CLT in the architecture community was intermediate. This group mentioned that the awareness has been steadily growing over the past five years as a consequence of the increased publicity of CLT systems by organizations that promote the use of wood in the U.S.

One participant of the study with a background in engineering stated that the level of awareness is *"Higher in the architectural area [*as*] they tend to know about it, whereas from the engineering standpoint, it is lower, [*since*] they are less knowledgeable about wood materials."* The same participant mentioned that the national engineering curriculum does not include in-depth information of wood as a material. For this reason, engineers tend to be less aware of wooden materials, and thus more inclined to choose other materials which are widely and intensively covered in their educational programs. One manufacturing representative also pointed out that the level of awareness about CLT depends on the location. According to this respondent, in regions with more tradition in wood-based construction (e.g. Pacific Northwest), a higher level of awareness exists, while in regions with no wood construction tradition (e.g. Southeast) awareness is notably lower.

Barriers to the adoption of CLT in the U.S.

A majority of respondents indicated that the main barrier for the adoption of CLT in the U.S. was the fact that CLT-based systems are not included in the International Building Code (IBC, 2012). According to Blomgren (2012), designers who want to use CLT for a project must request permission from local authorities, but the multiple jurisdictions that come into play (city, state and country) with such requests complicate the process. One of the respondents, working at a national wood-based products research facility, mentioned that in the U.S., the American Wood Council created task committees to begin the process of adding "heavy timber" (e.g., CLT) to its National Design Specifications (NDS) in 2011. However, the extensive research and testing required for inclusion in the NDS typically takes several years, thus completion is not expected until late 2014. The same respondent, who is also part of the National Design Specification for Wood Construction Committee, stated that CLT is expected to be available nation-wide by 2015. Recently, Canada changed its Building Code to allow buildings made of wood up to six stories (in comparison, the UK, Norway and New Zealand place no height restrictions on "safely-made" wooden high-rise (Lehmann et al., 2011)). In the U.S., a limited effort by FPInnovations (a Canadian research institute) and APA (The Engineered Wood Association) has been undertaken towards removing code barriers and to regulate CLT construction. For this purpose, a U.S. - Canadian CLT Standard Committee was instituted and, in parallel, the American National Standards Institute (ANSI) approved the ANSI/APA PRG 320-2011 Standard (Standard for Performance-Rated Cross Laminated Timber) in December 2011. The ANSI/APA PRG 320 standard provides requirements and test methods for quality (wood, adhesives, and dimension tolerances), resistance (bending, modulus of elasticity, shear and bonding) and appearance (architectural and industrial) of CLT (APA, 2012).

Another barrier to the adoption of CLT mentioned during the interviews was the availability of information and education about CLT. The participants representing the architecture sector indicated that, as one respondent put it, *"Architects and engineers are aware [of CLT] but [between] being aware [and] being proficient, there is [a] lack of education."* Another respondent added that *"It is going to take a little time to understand the product and probably [*there is a*] need of training, seminars, or similar activities, to get people more comfortable [*with CLT*]."* Such comments are most likely related to the previously discussed lack of education in wood materials in many education curricula, especially in engineering. In that sense, according to two respondents, architects tend to be more receptive for wood-based construction systems, while engineers seem to prefer concrete and steel due to their educational background.

The limited availability of CLT in the national market was also seen as an important barrier to the successful adoption of the material in the U.S. market. At the moment, CLT is not currently produced commercially in the U.S. for structural purposes, making it difficult for users to choose CLT over other materials which are more readily available. Currently, opting for a CLT solution would imply extra transportation costs, since the panel would have to be imported from Europe or Canada. One respondent stated that *"If you don't have any capacity or any production in the United States then […] no one knows about this product."*

Another potential barrier to the successful adoption of CLT systems in construction is the widely perceived disadvantage of wood as a building material. Typical concerns center on fire requirements and insect-attack problems. More generally, wood is seen as a risky option in comparison to concrete, steel, or masonry. Furthermore, social acceptance also plays a vital role in the implementation of any innovation (Yuan et al., 2011) and changes in behavior have frequently been listed as the number one barrier to the adoption of new products (McKenzie-Mohr, 1995, Lehmann, 2012).

Technical issues of CLT panels as a threat to successful adoption were mentioned by one respondent from the research community. This individual pointed out that lateral and shear design of CLT still needs considerable research. One of the U.S. manufacturing representatives mentioned issues in the manufacturing sector as a potential barrier to successful adoption. This person explained that their company's main struggle is to get the necessary equipment for the production of CLT from Europe; as such equipment cannot be currently procured from U.S. manufacturers.

Cost-competitiveness of CLT

When asked about the competitive position of Cross-Laminated Timber (CLT) compared to traditional building systems, a majority of experts interviewed coincided that CLT is cost-competitive compared to concrete structures. This is consistent with preliminary research conducted by FPInnovations and published in the U.S. version of the CLT Handbook (2013). CLT's cost competitiveness is mainly driven by the short construction times compared to more traditional building methods (concrete or steel). Lend Lease, the developers of the first 10-story wooden apartment building in Melbourne Australia, compared the 38 days and 6 technicians it took to build the Forte building in CLT with the approximately 20 weeks and 30 technicians that would have been required to build an equivalent concrete structure (Lend Lease, 2013).

Respondents were skeptical however when comparing cost effectiveness of CLT with wood-frame systems. Four participants mentioned that they think it unlikely that CLT systems would ever be cost-competitive with traditional wood-frame systems, as the volume of wood required for the panels is estimated to be three times the volume used in a wood-frame structure. One respondent who has been performing cost and material requirements comparisons for CLT and wood-frame systems stated that the volume of wood required greatly depends on the type of building. The taller the building, the more load the panels will have to support, thus the thicker the elements will need to be. Thus, an industrial one-story building will demand fewer resources than a 10-story apartment building.

A manufacturing representative from Europe mentioned that the cost-competitiveness of CLT should not only be evaluated on the initial investment, but that a long-term calculation reveals even more favorable economics: *"[CLT is] cost-competitive because it already has thermal insulation, […] and for sure it might be a little bit more expensive in the beginning, but when you also include the maintenance costs it turns out to be absolutely cost-competitive."* Hameury (2006) showed that massive timber enclosures require less insulation materials to achieve comfortable inner temperatures if designed and installed correctly. CLT panels require little to no maintenance (Sutton, 2011). One of the main reasons for the need of maintenance is moisture-related problems. Successful moisture management starts with minimizing the amount of water brought in by the material during construction. Thus, the manufacture of CLT, as regulated by the ANSI/APA PRG 320-2011 standard (APA, 2011), follows established protocols for measuring the moisture content of CLT panels, to minimize the occurrence of moisture problems in the enclosure once the panels are installed.

Potential applications for CLT

Cost-competitiveness is to a large extent related to the building type. When experts were asked about the types of buildings for which Cross-Laminated Timber (CLT) would be most suitable, all respondents agreed that CLT-based construction systems should be more suitable for high-rise buildings over six stories, where the panels can replace less environmentally-friendly materials, such as concrete or steel. As mentioned before, CLT systems offer structural performance comparable to concrete for high-rise buildings, while reducing construction time considerably, since CLT shortens the waiting times until another floor can be build. While concrete needs to be cured for at least 28 days before 90% of the material's final strength is reached and the formwork for the next floor can be placed (Kosmatka, 2011), CLT does not require any curing time on the construction site.

Four of our ten respondents mentioned that another suitable use for CLT as an alternative to concrete was for large box-like industrial or commercial buildings (e.g., supermarkets, industrial buildings, convention pavilions, or sport venues). Those uses require long spans and tall walls that can be built cost-competitively with CLT-based systems.

Respondents working in research-related fields saw a large potential for CLT due to its alleged superior structural performance. These respondents mentioned that CLT-based systems could find a niche market as a construction material for buildings subjected to seismic forces. Also, two experts stated that massive timber (i.e., CLT) is well suited for earthquake prone areas, while another expert mentioned that CLT could also be used in regions where hurricane and tornado shelters are required. For extreme conditions like hurricanes and tornados, the lightness of a structure reduces the lateral loads, and wood buildings consequently have more flexibility than concrete or masonry structures, which are more prone to collapse (Schmitt, 2012; Tonks and Chapman, 2009). Numerous joints and connections in CLT, as well as the attachment of sheathing, provides countless load paths in the event of lateral forces. If one connection is overloaded, its share of the load can be picked up by adjacent connections (Canadian Wood Council, 2003), creating a surprisingly strong structure.

None of the respondents considered the single-family residential building sector as a potential market for CLT systems. Some elaborated that this sector is dominated by wood-frame construction systems, which are highly efficient and cost-effective for this application.

Potential for adoption of CLT

The group of CLT experts interviewed for this study was asked about the potential of nationwide adoption of CLT in the U.S. Even though eight of the respondents agreed that the system had a great potential to become the next environmentally-friendly alternative to traditional materials like concrete, masonry, or steel, there were a few exceptions. Two researchers and one architect agreed that the adoption was most likely to depend on the region, in a similar manner as awareness of CLT. As pointed prior, according to our respondents, adoption is more likely to occur in areas where the tradition of constructing with wood is stronger. In those regions, the public and construction professionals have less prejudice towards wood-based construction systems and are more open to accept new products. However, respondents believed that the adoption of CLT will be more of a challenge in regions where concrete, steel, or masonry are traditionally used. As one researcher stated, the adoption of CLT *"…Would face challenges in the South because of [the concern for] termites, this might require [chemically] treating CLT. But in the Northern, Eastern, and Western regions of the United States, I think there is a big potential for buildings constructed with CLT*."

One of the respondents, a U.S. researcher, mentioned that the potential for CLT adoption was highly related to the "green building" movement, indicating that this movement is the "*wild card*" to the successful adoption of massive timber (e.g., CLT) elements. Espinoza et al. (2012) stated that this environmental movement is driven by market demand, thus if the "green building" movement keeps growing, there is the possibility that CLT systems will gather momentum and be widely used in the country in the near future. In this context, the implementation of green building credit programs such as LEED from the Green Building Council, will greatly promote the use of wood (Qi et al., 2010; Atlee, 2011). LEED establishes a system where buildings need to satisfy certain requirements to earn points to achieve different levels of certification (U.S. Green Building Council, 2013). One of these requirements relates to the materials chosen for the building envelope, encouraging the use of sustainable materials (such as wood from certified sources) and waste reduction (U.S. Green Building Council, 2013; Wang et al., 2013). CLT-based systems are uniquely positioned to fare well on both of these requirements. However, one respondent voiced doubts about whether the conditions needed for the successful adoption of CLT-based construction systems at a national level (national availability, overcome people's misconceptions about wood, acceptance in the engineering community, among other things) will ever be met. Should this respondent's worries materialize, CLT's future in the U.S. might just be as a small niche market product.

Conclusions

The main goal of this research was to assess the market potential and barriers to adoption of Cross-Laminated Timber (CLT) in the United States. Specifically, this study assessed the level of awareness about CLT in the U.S. architecture and engineering community, their perceptions about CLT, and their willingness to adopt CLT-based construction systems in the future. For this purpose, a series of semi-structured interviews were conducted with experts in the area of CLT manufacturing and construction systems.

Results show that the main benefits of CLT-based systems come from using a natural, renewable resource (wood) as opposed to materials which manufacturing is highly energy-intensive and requires non-renewable raw materials, like concrete or steel. Another important benefit of CLT-based systems over traditional construction systems (e.g., concrete, masonry, steel) is the shorter construction time needed, as CLT is a prefabricated system, in which panels come to the construction site ready to be installed. Thus, CLT-based systems reduce labor time, on-site waste, accidents and disturbances to the site's surroundings; all of which have a positive effect on total construction costs. Structurally, CLT offers performance comparable with concrete or steel, yet with a reduction of the weight. CLT's layered configuration grants the panels good rigidity, stability, and mechanical properties, allowing CLT to be used as walls, floors, roofs, elevator shafts, stairways, to name a few possible applications.

Experts interviewed mentioned that CLT has some technical drawbacks such as its acoustic and vibration performance, especially when the acoustic insulation and underlayment needed are not included in the design. Another concern voiced by several respondents was the volume of wood utilized in the manufacture of CLT panels. According to one expert, CLT panels use three times more wood than a wood-frame system solution.

Regarding the level of awareness about CLT-based construction systems among architecture professionals, there was almost universal consensus among respondents that the awareness is still low in the U.S. Reasons suggested include the novelty of the system and regional variances. Two respondents indicated that professionals in areas with a larger tradition of wood-based construction appear to be more likely to be familiar with CLT-based systems. Also, a distinction between architects and engineers emerged in that architects tend to be more receptive to wood-based construction systems, while engineers lean towards concrete and steel, probably due to differences in the educational curriculum between those two professions.

Barriers to adoption of CLT-based construction systems in the U.S. mentioned by the respondents were Building Code compatibility, availability of CLT in the domestic market, and misperceptions about wood as a building material. In particular, the current absence of CLT manufacturing operations in the U.S. requires that CLT elements need to be imported from Canada or Europe, which adds to the total costs. Machinery for the production and the processing of CLT also needs to be imported, further adding to the costs. Other barriers noted were the perception that the public may have of CLT-based systems, since it uses a notably larger amount of wood than traditional wood-frame construction. Moreover, the decades-long perception by professionals and individuals about the lack of durability of wood was also seen as a possible barrier to the wide adoption of CLT-based construction system.

Responses regarding cost-competitiveness indicate that Cross-Laminated Timber can be a cost-competitive alternative to concrete structures, especially for buildings over six stories high. This is in part due to the dramatically reduced construction time needed for CLT-based systems. Most experts agreed that CLT is cost-competitive for high-rise commercial or multi-family residential buildings, and low-rise commercial and industrial buildings, where a wood-frame system cannot be used. Respondents also agreed that the system would not be cost-competitive for applications where light wood-frame construction can be used, such as in single and multi-family low-rise buildings, because of the volume of wood (and consequently its cost) required to manufacture the CLT panels.

Experts indicated that the future of CLT is promising and that the adoption of the system nationwide is going to happen. However some participants showed some skepticism based on their experience with the adoption of CLT-based systems in other parts of the world. These skeptics stated that CLT-based systems could end up finding a niche market in some regions while acceptance of the system will be rather difficult in regions with a tradition of construction in concrete, masonry, or steel. Success of CLT-based construction systems may also depend on the success of the environmental, “green” building movement, which has been one of the most promising proponents of CLT-based construction systems.

Chapter 3

Survey of the U.S. architecture community

Introduction

The goal of this part of the study was to assess the market potential and barriers to adoption of Cross-Laminated Timber (CLT) in the United States through a survey of potential adopters. The following specific objectives were defined: (a) estimate the level of awareness about CLT among architectural firms; (b) learn about the perceptions about the environmental, structural, and economic performance of CLT, and (c) assess the willingness to adopt CLT by the U.S. architecture community. Although interviews conducted for the first part of this study provided important in-depth information about experts' perspectives on CLT, their opinions do not necessarily reflect those from potential adopters of the system. Therefore, a web-based survey was conducted to gather information about the perceptions of national architecture firms, who are key players in the material selection for a construction project.

Methodology

A nation-wide survey of U.S. architectural firms was carried out with the purpose of learning about this community's perceptions and awareness about CLT. The survey was delivered through the internet, which is a cost-effective approach that allows reaching large geographic areas at an affordable cost (Dillman et al., 2009; Sue et al., 2012; Couper, 2008). There are several services that provide tools for the design, implementation, and data analysis of online surveys. For this study, the Qualtrics software was used (Qualtrics, 2013).

Given the importance of architects in the material selection process, they were the population of interest for this study. Based on the information from the interviews to experts (Chapter 2) and preliminary economic analysis conducted by FPInnovations (2013) that concluded that commercial buildings are the most adequate for CLT, a decision was made to focus on U.S. architectural firms that work primarily with commercial buildings, which includes office buildings, retail, hospitals, restaurants and hotels, among others.

As a first step in the survey process, the sample size was calculated and a list of U.S. architecture firms was compiled, using the online database managed by the American Institute of Architects (AIA, 2013). This association is the major professional association for licensed architects, according to personal communications with the Director of Component Communication & Resources of the AIA (AIA, 2013; Yu et al. 2007). The AIA's member directory provides search tools to generate lists of firms using criteria such as geographic location, type of building projects, and zip code. There are currently over 26,000 firms in the AIA's database, from a total of 37,510 architecture firms in existence, according to the U.S. Census Bureau (U.S. Census Bureau, 2013), thus representing about 69% of all architecture firms in the U.S.

Sample size determination

Choosing the sample size is a critical decision in any survey research. The objective is to select the smallest sample size that allows for an adequate confidence level and margin of error. The correct sample size will help decrease the occurrence of sampling error and sampling bias (Dillman, 2008). According to Dillman (2008), the sample size can be estimated as follows:

$$\text{Sample size} = \frac{Z^2\,s^2}{H^2}$$

Where Z is the inverse of the normal distribution, which at a desired level of confidence of 95 percent is 1.96. H represents the confidence interval, set at 5% for this research (H=0.05). To obtain the largest sample size (worst case scenario), s, which is the expected standard deviation, takes the value of 0.5.

$$\text{Sample size} = \frac{1.96^2 \times 0.5^2}{0.05^2} = 384$$

Assuming that 384 respondents corresponds to an expected response rate of 25%, an initial sample of 1,525 firms was calculated and rounded up to 1,600 firms. From a total of 2,376 architecture firms that work with commercial buildings in the U.S., the number of firms from each state to be included in the list was calculated as a proportion of the state's population.

Questionnaire development

A first draft of the survey questionnaire was developed using the results from preliminary interviews and the literature review as primary inputs (Chapter 2). The first version of the questionnaire contained 11 questions, 10 of which were of the multiple-choice variety, and one open-ended question (Appendix 2). The questionnaire covered the following topics:

- Company demographic information: location and size of company.
- Awareness of CLT in the Architecture Community: familiarity with CLT, how participants learned about the system.
- Perceptions towards CLT: how participants perceive the environmental, structural and economic benefits of the system.
- Willingness to adopt the CLT building system.

To assess clarity and relevance, the draft questionnaire was sent to six architects and two researchers with experience in survey design and implementation. These architects and experts were asked to evaluate the clarity and consistency of the questions, identify potential errors, and provide suggestions and recommendations. Based on this feedback, changes were made to the questionnaire.

The survey instrument included an introductory email to inform participants about the study and request their participation, including a link to access the web-based survey. The questionnaire started with a welcome page with information about the study as well as a confidentiality statement. Questions were grouped according to the topics mentioned above. A final "Thank you" message was presented to those participants who completed the questionnaire. Participants were also asked whether they were interested in having a summary of the survey results, and those who answered positively to this question were asked to provide an email address where they wanted the summary to be sent. The final questionnaire, associated materials, and a copy of the Institutional Review Board approval are located in Appendix 3.

Survey pretest

To identify issues that were overlooked during the questionnaire development and expert evaluation, which could potentially lead to misinterpretation or low response rate by respondents, a pretest was conducted (Hunt et al., 1982; Collins, 2003). The pretest was conducted by sending the survey to 50 U.S. architecture firms, which were picked from the list previously compiled (one randomly selected firm from each U.S. state). These companies were asked to provide feedback about the survey's clarity and potential errors. After four days, a reminder was sent to those participants that did not answered. Only four companies answered the pretest. It is hypothesized that the request for feedback discouraged or confused firms to complete the survey and to provide feedback, resulting in a low response rate. However, the analysis of the pretest responses did not suggest difficulty in completing the questionnaire and only minor changes in wording were made.

Survey implementation

A first email was sent to all companies in the distribution list on December 8th of 2013. Two reminder emails were sent to those participants that did not complete the questionnaire, one week and three weeks after the initial email. The survey was closed in January 15th of 2014, after five weeks of the initial email.

Data analysis

After the survey was closed, response data was downloaded to be analyzed using standard statistical techniques. Descriptive statistics and charts were calculated. Categorical data was evaluated using chi-squared tests. All tests were evaluated at a 0.05 alpha level. Excel (Microsoft, 2010) and SPSS (IBM, 2014) were used for the analysis.

Limitations

As with any other research method, there are limitations and potential sources of error (Dillman et al., 2009; Sue et al., 2012). The most important are listed below.

- Measurement error: survey question and answer options could lead to inaccurate data because certain answer options may be interpreted differently by participants. While this source of error cannot be eliminated, an attempt was made to minimize its magnitude by seeking the input and feedback from experts, and by doing a survey pre-test.
- Non-response bias: which means estimating a population characteristic based on a sample in which certain types of respondents are under or not represented. This was addressed by the sampling strategy and by testing for non-response bias.
- Coverage error: using the AIA database to compile the mailing list for this survey could introduce a source of coverage error, since not all U.S. architecture firms are associated with the AIA, and some differences may exist between companies that belong to this association and non-members.
- In order to make inferences about the relationship between firm location and respondents perceptions, a “multi-region” category was created, grouping those companies with operations in more than one region. Thus some region-related information was lost from those firms grouped into this category.
- Technical problems could also arise. Some respondents may be unable to complete the survey due to a browser freeze or server crash, resulting in missing data.
- Limitations inherent to any internet-based survey apply to this study (Dillman, 2009). Importantly, answers received represent the knowledge of a single professional in an architecture firm that may employ many individuals. Since the population of interest is comprised of architecture firms that work primarily with commercial buildings, conclusions do not necessarily apply to the entire architecture community.

Results and Discussion

Response rate

The questionnaire was sent to a total of 1,627 U.S. architecture firms. A total of 351 usable responses were received. Accounting for 19 firms that declined to participate, 5 firms that were not part of our targeted population (e.g., interior design, forensic architecture), 22 undeliverable emails and 33 incomplete surveys, the adjusted response rate was 22.7%. Figure 4 presents a timeline of the survey.

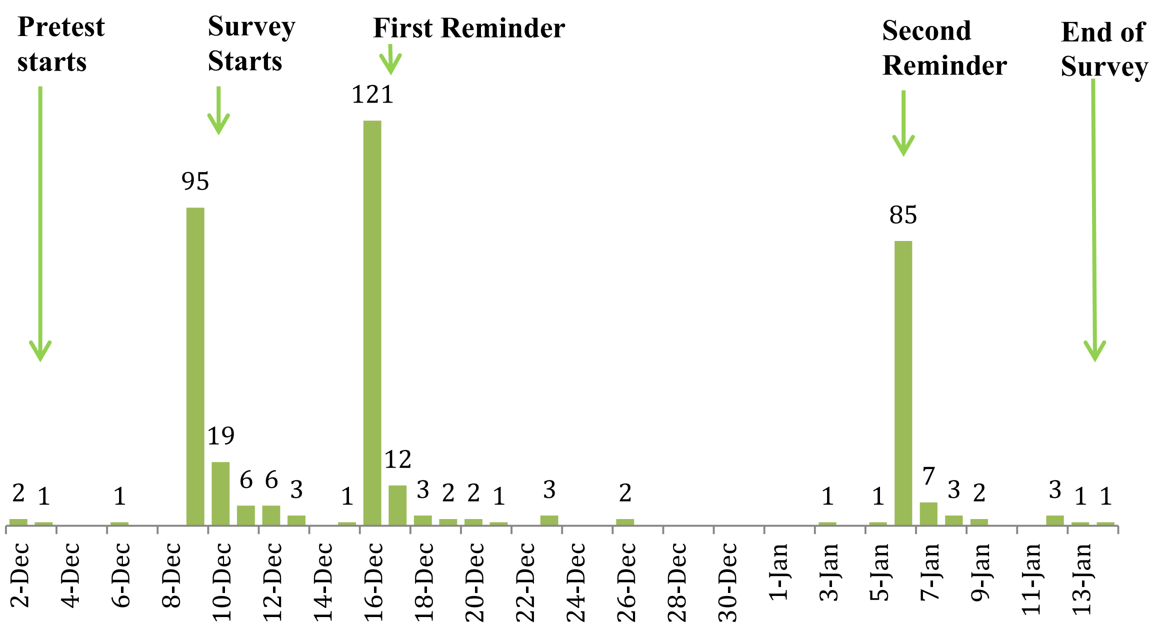


Figure 4. Survey timeline and number of responses received.

Non-response bias assessment

Non-response bias refers to error in estimating a population's characteristic based on a sample in which, due to non-response, certain types of participants are under- or not represented (Berg, 2005). Evaluating the occurrence and pattern of non-response bias in a sample is an essential step in the analysis of results obtained from a survey, since non-response bias limits the generalizations about a population that can be drawn from the results (Groves, 1989; Groves, 2002). For this research, the non-response bias was estimated by comparing early and late respondents. This practice is based on the assumption that there is a continuum in the likelihood of answering a survey, high for those that answer immediately after the first mailing, and zero for those that did not respond. Thus, late respondents can be used as a proxy for non-respondents (Lahaut et al., 2003; Etter and Perneger, 1997).

Early respondents (those answering before the first reminder) and late respondents (those answering after the second reminder) were compared based on three attributes: firm location, firm size, and familiarity with CLT. The following table (Table 1) summarizes the count for each category, and presents the results from the statistical tests.

Table 1. Results of the non-response bias assessment.

	Criteria	Early Responses		Late Responses	
Code	**Firm Location**	**n**	**%**	**n**	**%**
1	Northeast	17	15.0%	13	13.8%
2	South	36	31.9%	31	33.0%
3	Midwest	20	17.7%	19	20.2%
4	West	22	19.5%	15	16.0%
5	Alaska	0	0.0%	0	0.0%
6	Hawaii	1	0.9%	0	0.0%
7	Multi-region	17	15.0%	16	17.0%
	TOTAL	**113**		**94**	
Pearson's chi-squared test: χ^2**=1.5 p-value=0.906** ($p>0.05$)					
Code	**Firm Size**	**n**	**%**	**n**	**%**
1	1 to 4	63	56.3%	48	51.1%
2	5 to 9	23	20.5%	20	21.3%
3	10 to 19	12	10.7%	14	14.9%
4	20 to 99	11	9.8%	11	11.7%
5	100 or more	3	2.7%	1	1.1%
	TOTAL	**112**		**94**	
Pearson's chi-squared test: χ^2**=1.8 p-value=0.766** ($p>0.05$)					
Code	**Familiarity with CLT**	**n**	**%**	**n**	**%**
1	Very familiar	6	4.5%	2	2.1%
2	Somewhat familiar	35	30.2%	45	46.3%
3	Not very familiar	48	43.1%	31	33.6%
4	Have not heard about it	24	22.0%	15	15.7%
	TOTAL	**113**		**94**	
Pearson's chi-squared test: χ^2**=7.1 p-value=0.068** ($p>0.05$)					

Note: n=number of responses
%=percentage of responses

Early and late respondents were compared using Pearson's chi-squared tests with a significance level of 0.05 (Table 1). The test performed under the location criteria resulted in a chi-squared value of χ^2=1.5 and a p-value of 0.906 ($p>0.05$), indicating that there is no relationship between the time of the response and the location of the firm. The evaluation of association between time of response and size of the company also showed no statistically significant association between these two variables (χ^2=1.8 and p-value =0.766). Similarly, no significant relationship was found between timing of the response and level of awareness (χ^2=7.1 and p-value of 0.068). Therefore, it was concluded that no significant differences existed between respondents and non-respondents on the three dimensions of comparison.

Demographics

Respondents were asked to indicate the location of their firm (U.S. region) and the firm size in number of employees. Participants were able to check more than one location to indicate that they had operations in more than one region. Firms with operations in more than one region were grouped into a new category, called “Multi-region,” to facilitate the analysis.

From the total 351 respondents, almost a third (30.2%) indicated that their firm was located in the Southern region, while, the smallest percentage (0.6%) was identified as located in Hawaii. Regarding the firm size, more than half (52.4%) were small firms (1 to 4 employees), while only 3.4% of the respondents represented companies with 100 or more employees. Table 2 shows the counts and percentages for each region and firm size.

Table 2. Survey participants’ firm location and size (by number of employees). N=351.

U.S. Region	**n**	**%**
Northeast	51	14.5%
South	106	30.2%
Midwest	63	17.9%
West	74	21.1%
Alaska	0	0.0%
Hawaii	2	0.6%
Multi-region	55	15.7%
Firm size	**n**	**%**
1-4 employees	184	52.4%
5-9 employees	75	21.4%
10-19 employees	37	10.5%
20-99 employees	42	12.0%
100 or more employees	12	3.4%

Notes: n=number of responses
%=percentage of responses
Firm size percentages add up to less than 100% because one firm did not answer this question.

Importance of materials characteristics

Respondents were asked to rate the importance of a number of characteristics when specifying a construction material. Table 3 shows the count of responses and percentages obtained for each characteristic. Results indicate that the most important characteristics that architects look for in a construction material are structural performance (98.6% of respondents rated this attribute as "very important" or "important"), durability (97.8%), economic performance (95.2%), aesthetics (94.0%), and availability in the market (90.0%). Fire performance, environmental performance, and cost of post construction maintenance have a high importance with 88.0%, 85.2%, and 83.2% of respondents rating this attribute as "very important" or "important". Earthquake performance and the possibility of earning LEED credits were rated low in the same importance scale (45.0% and 25.0% of respondents, respectively, rated these characteristics as "very important" or "important" in material selection).

It is presumed that features such as structural performance and durability, which are also related to the structural performance of a structure, were rated the highest because of concern for the occupants' safety and the liability implications that a structural failure might have (Pealer, 2007; Mahler, 2014). The same can be said for fire performance, which was also between the characteristics rated with the highest importance. Earthquake performance was rated as one of the least important material characteristics, which may be explained by the uneven distribution of seismic activity, thus regions with more activity would tend to rate this feature as more important. The importance of features related to the economic performance, such as availability in the market and maintenance costs are highly rated possibly because of their influence on the economic feasibility of a development and its long-term success over the years. In general, architects tend to look for the best quality-cost relationship that could not only reduce the construction costs but also the operation and maintenance costs (Mann, 1992; Bowen et al., n.d; Mahler, 2014).

Table 3. Survey participants' responses regarding the importance of material characteristics when selecting a construction material. N=351.

Please rate the importance of the following characteristics at the time of specifying a construction material								
Characteristic	**Very Important**		**Important**		**Somewhat Important**		**Not at all important**	
	n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Environmental performance	126	35.9%	173	49.3%	45	12.8%	5	1.4%
Structural Performance	290	82.6%	56	16.0%	3	0.9%	1	0.3%
Economic performance	193	55.0%	141	40.2%	15	4.3%	1	0.3%
Aesthetics	209	59.5%	121	34.5%	16	4.6%	2	0.6%
Fire performance	152	43.3%	157	44.7%	34	9.7%	3	0.9%
Earthquake performance	59	16.8%	99	28.2%	117	33.3%	72	20.5%
Availability in the market	125	35.6%	191	54.4%	32	9.1%	1	0.3%
Acoustic performance	26	7.4%	151	43.0%	148	42.2%	22	6.3%
Durability	215	61.3%	128	36.5%	5	1.4%	1	0.3%
LEED credits	17	4.8%	71	20.2%	180	51.3%	81	23.1%
Cost of post-construction maintenance	100	28.5%	192	54.7%	54	15.4%	3	0.9%

Note: n=number of responses
%=percentage of responses
Sum of percentages for each characteristic is not 100% because not all participants rated all the items.

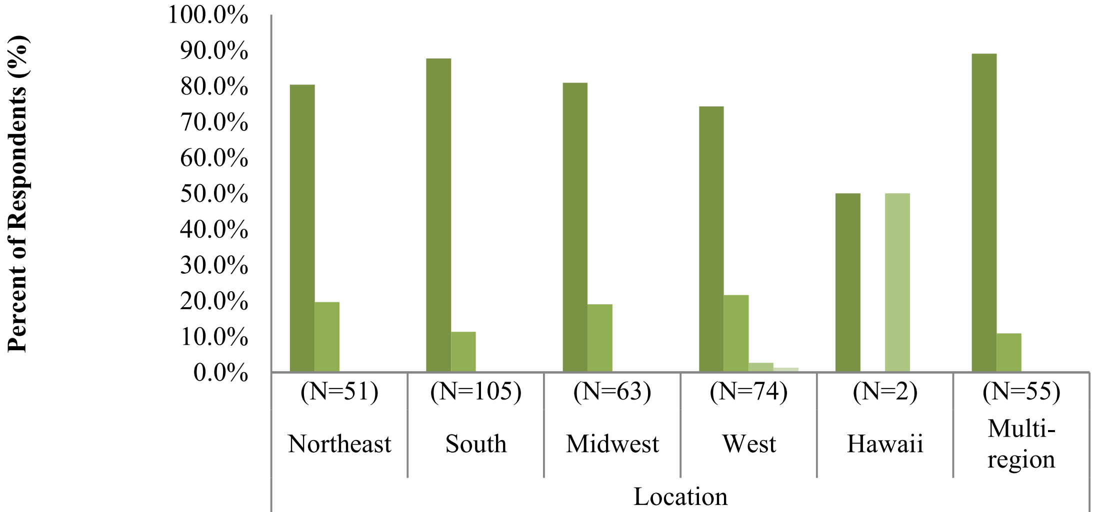
Chi-squared tests (alpha=0.05) were performed for each characteristic to determine if location and size of a firm have an effect in the way each characteristic was rated. Table 4 shows the results from this analysis. Statistically significant differences were identified in responses from firms in different locations for structural and earthquake performance and availability in the market. In regards to firm size, responses were only significantly different for LEED credits.

Table 4. Results from chi-squared tests to assess the relationship between participants' firm location and size, and the stated importance of construction material characteristics.

Characteristic - Firm Location	χ^2	P-value
Environmental performance	11.9	0.686
Structural Performance	71.8	<0.001*
Economic performance	15.7	0.402
Aesthetics	13.1	0.588
Fire performance	22.9	0.085
Earthquake performance	76.2	<0.001*
Availability in the market	29.1	<0.001*
Acoustic performance	13.0	0.599
Cost of post-construction maintenance	10.0	0.817
Durability	8.7	0.889
LEED Credits	17.7	0.274
Characteristic - Firm Size	χ^2	**P-value**
Environmental performance	9.0	0.701
Structural Performance	11.0	0.524
Economic performance	6.0	0.914
Aesthetics	17.2	0.305
Fire performance	5.9	0.920
Earthquake performance	20.5	0.057
Availability in the market	15.6	0.209
Acoustic performance	8.3	0.759
Cost of post-construction maintenance	7.8	0.800
Durability	17.3	0.138
LEED Credits	24.2	0.019*

* Denotes statistical difference at alpha=0.05.

Further analysis was carried out for those characteristics in which the chi-squared tests (Table 4) showed significant differences. Figure 5 shows the percent of respondents by region and how they rated the importance of structural performance of building materials. A high percent of architects in all regions considered this attribute to be "very important" (82.6%, Table 3). However, an even higher percentage of firms with operations in more than one region (Multi-region) and firms in Southern states considered structural performance to be "very important" (89.1% and 87.7% indicating that structural performance is "very important," Figure 5).

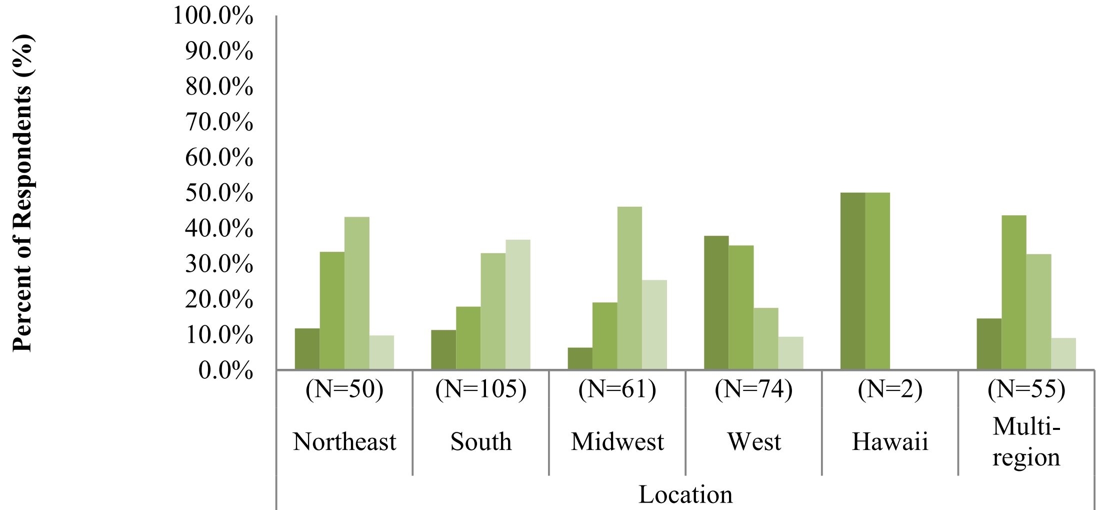


	(N=51) Northeast	(N=105) South	(N=63) Midwest	(N=74) West	(N=2) Hawaii	(N=55) Multi-region
Very Important	80.4%	87.7%	81.0%	74.3%	50.0%	89.1%
Important	19.6%	11.3%	19.0%	21.6%	0.0%	10.9%
Somewhat Important	0.0%	0.0%	0.0%	2.7%	50.0%	0.0%
Not at all Important	0.0%	0.0%	0.0%	1.4%	0.0%	0.0%

* Percentages calculated based on total respondents from each region that rated structural performance.

Figure 5. Geographic distribution of firms rating the importance of structural performance in building material selection.

When comparing how earthquake performance is perceived in the different regions, more firms located in the western regions and Hawaii consider earthquake performance as "very important" in material selection than in other regions (37.8% and 50.0% of respondents, respectively, about three to four times the percentages in all other regions). This is not surprising as these regions experience seismic events more frequently and intensely (Koyanagi, 1976; Dieterich, 1996; Ward, 1994).

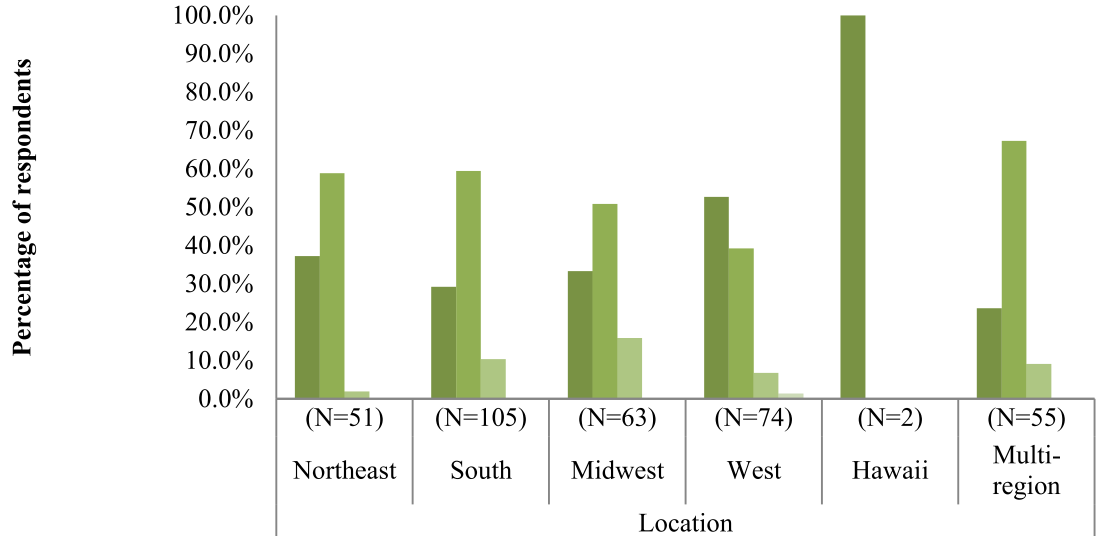


	(N=50) Northeast	(N=105) South	(N=61) Midwest	(N=74) West	(N=2) Hawaii	(N=55) Multi-region
Very Important	11.8%	11.3%	6.3%	37.8%	50.0%	14.5%
Important	33.3%	17.9%	19.0%	35.1%	50.0%	43.6%
Somewhat Important	43.1%	33.0%	46.0%	17.6%	0.0%	32.7%
Not at all Important	9.8%	36.8%	25.4%	9.5%	0.0%	9.1%

* Percentages calculated based on total respondents from each region that rated earthquake performance.

Figure 6. Geographic distribution of firms rating the importance of earthquake performance in building material selection.

Figure 7 shows the percent of respondents by region and how they rated the importance of availability in the market when selecting a building material. Unanimously, all respondents from Hawaii considered this attribute to be “very important” (100.0%). However, only 2 companies from that region responded this survey. It can be presumed that the availability in the market is an important issue for architects in Hawaii, since the logistics’ cost to bring construction materials from out of state are elevated (CRE, 2006). Availability in the market was rated as “very important” or “important” by 96.1% and 84.1% of those respondents in the Northeastern and Midwestern regions, respectively.

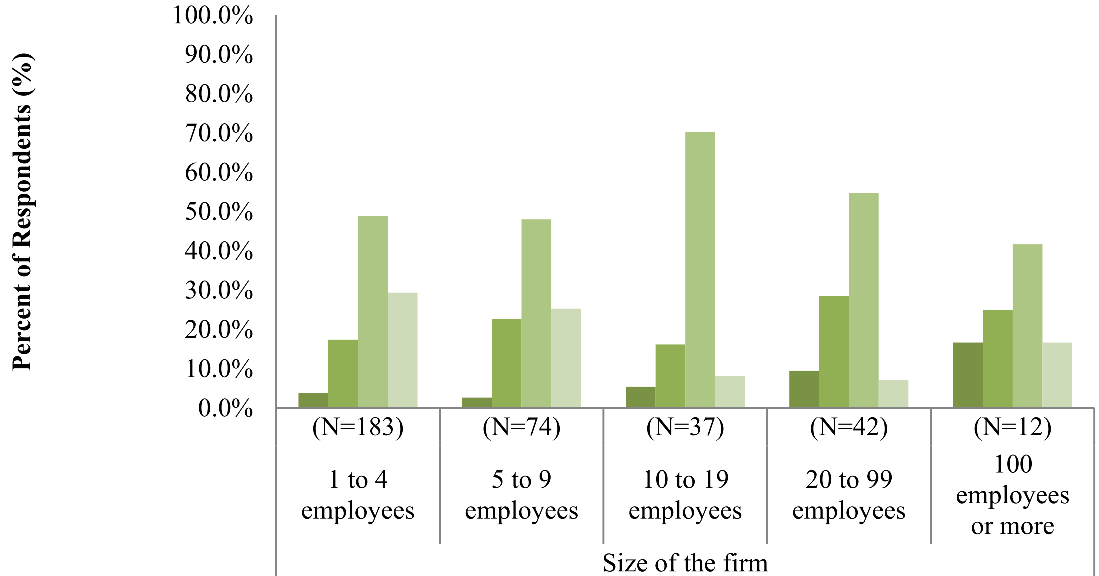


	Northeast	South	Midwest	West	Hawaii	Multi-region
Very Important	37.3%	29.2%	33.3%	52.7%	100.0%	23.6%
Important	58.8%	59.4%	50.8%	39.2%	0.0%	67.3%
Somewhat Important	2.0%	10.4%	15.9%	6.8%	0.0%	9.1%
Not at all Important	0.0%	0.0%	0.0%	1.4%	0.0%	0.0%

* Percentages calculated based on total respondents from each region that rated availability in the market.

Figure 7. Geographic distribution of firms rating the importance of the availability of the material in the market while selecting a building material.

Figure 8 shows the results obtained when comparing size of firm and the importance placed upon LEED credits. A greater percentage of large firms (100 or more employees) rated the importance of LEED credits as "very important" than small firms, defined as firms with 1 to 4 employees (16.7% of the largest firms compared to 3.8% of the smallest firms). As Bansal et al. (2000) states, in the world of large companies' competitiveness, environmental responsibility is used as a competitive advantage. In this sense, when planning for a new company office or the retrofit of their existing ones, some companies are willing to take a more environmentally-friendly approach for their construction (Esty et al., 2009). Large architecture firms are usually commissioned with these large projects, because of their ability to handle the complexities of such undertakings, thus it is presumed that these architecture firms would rate the importance of LEED credits higher that smaller firms.



	1 to 4 employees (N=183)	5 to 9 employees (N=74)	10 to 19 employees (N=37)	20 to 99 employees (N=42)	100 employees or more (N=12)
Very Important	3.8%	2.7%	5.4%	9.5%	16.7%
Important	17.4%	22.7%	16.2%	28.6%	25.0%
Somewhat Important	48.9%	48.0%	70.3%	54.8%	41.7%
Not at all Important	29.3%	25.3%	8.1%	7.1%	16.7%

* Percentages calculated based on total respondents from each firm size that rated LEED performance.

Figure 8. Distribution of respondents' firm size according to the rated importance of LEED credits potential in building material selection.

Level of awareness of CLT among architecture firms

One of the main objectives of this research was to determine the level of awareness about CLT in the U.S. architecture community. Participants were asked to indicate their familiarity with CLT. Table 5 shows the results for this question. A "skip logic" was set up in the questionnaire in a way that those answering that they "have not heard about CLT" were directed to the end of the survey, since the following questions required some knowledge about CLT. For this reason, after this question, the base number to calculate all percentages was changed to 286, since 65 respondents were dropped from the analysis.

Overall, only 4.3% of respondents indicated being "very familiar" with CLT, while 18.5% said they "have not heard about CLT." A combined 76.9% of respondents indicated being “somewhat familiar” or “not very familiar” with CLT, which suggests that, while these participants know about the existence of CLT, they consider their knowledge as superficial. This indicates that there is a need for education and training about CLT in the architecture community if this product is going to be more widely adopted in the U.S.

Table 5. Survey participants’ responses regarding their familiarity with CLT. N=351.

How familiar are you with Cross-Laminated Timber (CLT), also known as "Cross-Lam", "X-Lam" or "Massive Tiber"?		
Awareness	**n**	**%**
Very familiar	15	4.3%
Somewhat familiar	133	37.9%
Not very familiar	137	39.0%
Have not heard about it	65	18.5%

Note: n=number of responses
%=percentage of responses
Sum of percentages is not 100% because one participant did not answer this question

Follow-up Pearson’s chi-squared tests were performed to evaluate if a relationship existed between location of a firm and its size and the indicated level of awareness about CLT. Test results indicate that there is no significant relationship between firm location and level of awareness (χ^2=21.5 and p-value=0.118). Similarly, no significant relationship was found between firm size and the stated level of awareness (χ^2=8.1 and p-value=0.771).

To assess how firms learn about CLT and evaluate which methods of communication are more efficient for this type of audience, architects were asked to indicate how they heard about CLT for the first time. Results reported in Table 6 show that most firms learned about CLT from magazines and the internet (42.3% and 20.3%, respectively), and 17.5% at conferences, seminars or workshops. Although magazine names were not asked, it is hypothesized that architectural magazines were the source of the information. Least mentioned methods of communication were: radio, television, newspaper and word-of-mouth, each of them selected by less than 1% of the respondents. Respondents were also given the option to indicate whether they heard about CLT from another source. Eight respondents indicated that they learned about CLT from a “consultant engineer.” This suggests that engineers could be a population of interest to promote CLT, as they might influence architects’ decisions when it comes to deciding on a structural system.

Table 6. Survey participants' responses when asked about how they heard about CLT. N=286.

How did you hear about Cross-Laminated Timber for the first time?		
Media	**n**	**%**
Internet	58	20.3%
Television	1	0.3%
Newspaper	2	0.7%
Magazine	121	42.3%
Academic Journal	24	8.4%
Radio	0	0.0%
Relative of friend	3	1.0%
Conference/Seminar/Workshop	50	17.5%
Other	52	18.2%

Note: n=number of respondents
%=percentage of responses
Multiple answers were possible.

Perceptions about CLT

The success of a product depends on its ability to satisfy customers' needs and how these customers perceive the product. In marketing, perceptions are fundamental because what consumers feel and believe about a product can be just as important as what that product actually provides in terms of performance (Cooney, n.d.). Therefore, it is essential to learn how potential consumers view CLT's characteristics as a building material (Armstrong et al. 2013). With this purpose, participant firms were asked to evaluate CLT based on eleven criteria.

Results, in Table 7 show that 67.1% of responding firms considered that CLT had either "excellent" or "good" environmental performance. Results also indicate that a majority of respondents have a positive perception of CLT's structural performance: 22.7% graded CLT's structural performance as "excellent" and 45.8% as "good." Other highly-ranked characteristics were the aesthetic properties of CLT, which were ranked as "excellent" by 19.9% of respondents and "good" by 42.3% of respondents. Only 1.7% of respondents indicated that CLT's appearance was below average and poor. Wood is not only considered an excellent building material for its mechanical properties, but also because it is visually appealing (Dilem, 1992; Janin, 1994).

Table 7. Survey participants' responses regarding the perceived CLT's performance. N=286.

Please rate the following features of Cross-Laminated Timber, compared with other materials (e.g. steel, concrete).												
Features	**Excellent**		**Good**		**Average**		**Below average**		**Poor**		**Don't know**	
	n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Environmental performance	67	23.4%	125	43.7%	19	6.6%	1	0.3%	1	0.3%	72	25.2%
Structural Performance	65	22.7%	131	45.8%	26	9.1%	0	0.0%	0	0.0%	64	22.4%
Economic performance	24	8.4%	85	29.7%	50	17.5%	16	5.6%	3	1.0%	107	37.4%
Aesthetics	57	19.9%	121	42.3%	41	14.3%	4	1.4%	1	0.3%	61	21.3%
Fire performance	15	5.2%	89	31.1%	66	23.1%	8	2.8%	3	1.0%	103	36.0%
Earthquake performance	16	5.6%	78	27.3%	44	15.4%	2	0.7%	0	0.0%	144	50.3%
Acoustic performance	14	4.9%	78	27.3%	55	19.2%	4	1.4%	2	0.7%	131	45.8%
Cost of post-construction maintenance	11	3.8%	66	23.1%	67	23.4%	12	4.2%	1	0.3%	128	44.8%
Durability	21	7.3%	97	33.9%	54	18.9%	14	4.9%	0	0.0%	98	34.3%
LEED credits	33	11.5%	91	31.8%	27	9.4%	2	0.7%	1	0.3%	130	45.5%

Note: n=number of responses
%=percentage of responses
Sum of percentages for each feature is not 100% because not all participants rated all the items.

The economic performance of CLT is perceived as "excellent" or "good" by 38.1% of respondents, even though the product is not yet available in the market. This could possibly be related to the fact that wood construction is usually more economic than other materials. Results from the interviews to experts conducted for the first part of this study suggested that it is unlikely that CLT systems would be cost-competitive against traditional wood-frame systems, as the volume of wood required for the panels is about three times that used in a wood-frame structure.

Fire performance was ranked as "excellent" or "good" by 36.3% of respondents, and "poor" or "below average" by 3.8% of respondents. Over the past years many studies have confirmed that the fire behavior of massive timber elements like CLT approaches that of concrete's, providing excellent fire resistance because of wood's unique charring properties (FPInnovations, 2011; FPInnovations, 2013; Stone et al., 2013; Fragiacomo et al., 2013; Schmid, 2010).

CLT was ranked as low-performing in post-construction maintenance, given that only 26.9% of respondents indicated that they perceived CLT's performance on this attribute as "excellent" or "good" (Table 7). This can be understood in light of Lehmann's comments (2011), that a sizable percentage of individuals still do not completely trust the qualities of wood as a building material. This in turn can be traced back to the common perception that wood is less durable than other materials due to its organic nature, which makes it more susceptible to decay. However, Hameury (2006) and Sutton (2011) showed that if designed and installed correctly, CLT panels require little to no maintenance. When asked about durability of CLT, 41.2% of respondents indicated that its performance was "excellent" (7.3%) or "good" (33.9%) and 4.9% indicated that CLT's durability was "below average" or "poor."

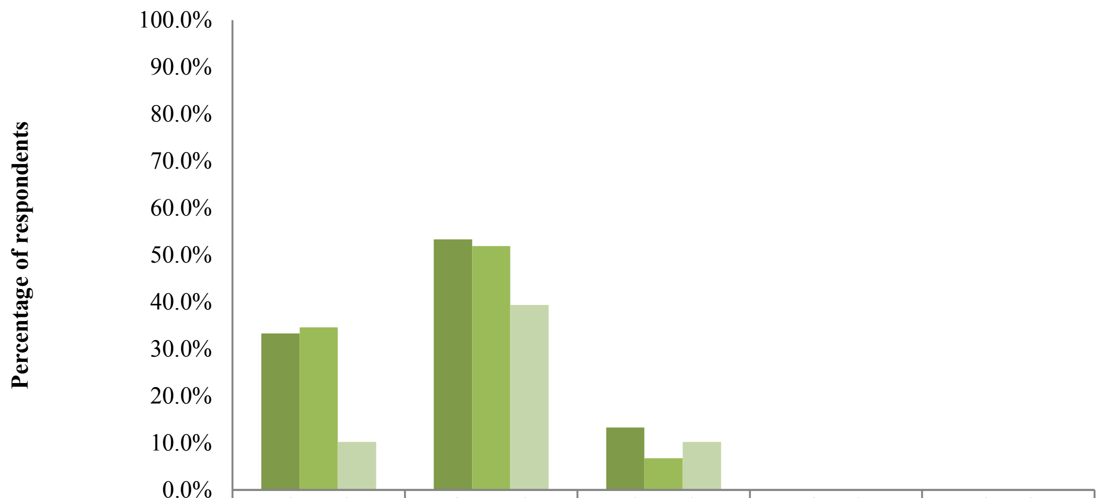
It is worth looking at those items where participants tended to select "I don't know" among the choices, as this may indicate areas where the need for information is greater. Relatively more participants indicated lack of knowledge in earthquake and acoustic performance (selected by 50.3% and 45.8% of participants respectively) than for structural (22.4%), environmental performance (25.2%), and aesthetics (21.3%).

The relationship between the level of awareness and the way respondents rated their perceptions on CLT performance was analyzed by performing chi-squared tests. According to the results (Table 8), the only significant relationship occurs between awareness and perception of CLT's structural performance, meaning that the more familiar respondents were about CLT, the better they perceived its structural performance (86.6% of respondents that are "very familiar" with CLT stated that its structural performance was "excellent" or "good."). This is illustrated in Figure 9.

Table 8. Results from chi-squared tests to assess the relationship between participants' level of awareness with CLT and the ratings given to CLT's performance on a number of characteristics.

Characteristic-Awareness	χ^2	p-value
Environmental performance	14.6	0.065
Structural Performance	12.0	0.017*
Economic performance	9.8	0.275
Aesthetics	13.1	0.106
Fire performance	10.1	0.256
Earthquake performance	12.4	0.052
Acoustic performance	12.0	0.150
Cost of post-construction maintenance	11.8	0.157
Durability	10.7	0.097
LEED Credits	8.5	0.380

* Denotes statistical difference at alpha=0.05.



	(N=65) Excellent	(N=131) Good	(N=25) Average	(N=0) Below Average	(N=0) Poor
Very familiar	33.3%	53.3%	13.3%	0.0%	0.0%
Somewhat familiar	34.6%	51.9%	6.8%	0.0%	0.0%
Not very familiar	10.2%	39.4%	10.2%	0.0%	0.0%

* Percentages calculated based on total respondents from each familiarity category that rated structural performance.

Figure 9. Distribution of respondents' perceptions regarding the structural performance of CLT according to the level of awareness.

Perceived barriers to CLT adoption

When asked about the perceived barriers to the future implementation of CLT in the U.S. (Table 9), 94.1% of respondents indicated that availability of the product in the national market is a "large barrier" or "may be a barrier" (Table 9). Out of the 286 respondents, 62.2% stated that the compatibility with the Building Code could also hinder the adoption of CLT. According to Blomgren (2012), designers who want to use CLT for a project must request permission from local authorities, but the multiple jurisdictions that come into play (city, state and country) in such requests complicate the process. Information obtained from the first part of this research project (Chapter 2) indicate that the new 2015 International Building Code is set to include CLT as an alternative material, which will help lowering this barrier.

At the moment, CLT is not currently produced commercially in the U.S. for structural purposes, making it difficult for users to choose CLT over other, more readily available materials. Initial cost was also seen as a potential barrier to the implementation of the system in the U.S., with 90.9% of respondents indicating that cost is a "large barrier" or "may be a barrier" (Table 9).

Table 9. Survey participants' responses regarding the perceived barriers to the implementation of CLT in the U.S. N=286.

Which do you think are the most important barriers to adoption of Cross-Laminated Timber in the U.S.?						
Barrier	**Large Barrier**		**May be a barrier**		**Not a barrier**	
	n	**%**	**n**	**%**	**n**	**%**
Amount of wood required	17	5.9%	155	54.2%	101	35.3%
Availability in the market	108	37.8%	161	56.3%	8	2.8%
Initial Cost	66	23.1%	194	67.8%	13	4.5%
Availability of technical information	59	20.6%	162	56.6%	56	19.6%
Compatibility with Building Code	75	26.2%	178	62.2%	22	7.7%

Note: n=number of responses
%=percentage of responses
Sum of percentages for each barrier is not 100% because not all participants rated all the items.

Table 9 shows that 77.2% of respondents said that the availability of technical information about the system "may be a barrier" or was a "large barrier." This represents an opportunity for organizations promoting the use of CLT to improve and increase the information available among possible adopters of the system. Results from the survey also indicate that 60.1% of respondents consider that the amount of wood required for the manufacture of the panels was a “large barrier” or “may be a barrier.” Respondents were given the opportunity to indicate other perceived barriers not listed in the questionnaire. The “Other” barriers listed were: “resistance to decay,” “fire performance,” “transportation issues,” “the complexity of the system when compared to other construction systems,” and “longer tradition that have been proven to work for a long time.”

The relationship between the level of awareness and the perceived barriers was analyzed by performing chi-squared tests. Results are presented in Table 10. According to the results the level of awareness specified does not seem to influence the perceptions about the barriers to CLT adoption.

Table 10. Relationship between level of awareness and barriers to adoption.

Barrier – Location	χ^2	P-value
Amount of wood required	7.8	0.095
Availability in the market	8.5	0.074
Initial cost	4.7	0.310
Availability of technical information	4.8	0.306
Compatibility with Building Code	0.34	0.987

*Denotes statistical difference

Perceived suitability of CLT for different building types

Architects were asked about their perceptions on the most appropriate types of building for the use of CLT. Table 11 summarizes the results to this question. From all the responses obtained, 51.0% of respondents indicated that CLT would be “very appropriate” for residential multi-family buildings while only 35.0% of respondents deemed CLT “very appropriate” for residential single-family buildings.

Regarding suitability of CLT for commercial buildings, 25.2% of the architecture firms surveyed indicated that CLT could be "very appropriate" for this type of buildings and 50.7% indicated that it could be "somewhat appropriate." Results also show that CLT was thought to be "very appropriate" or "somewhat appropriate" for government (48.4%) and transportation related buildings (44.4%). Four out of ten experts interviewed in the first part of the study (Chapter 2) mentioned that CLT would be a viable alternative to concrete for large box-like industrial buildings and commercial buildings, where users require long spans and tall walls that can be built cost-competitively with CLT-based systems. Respondents to the survey were allowed to indicate other suitable applications for CLT. The most frequent applications mentioned were religious buildings, such as churches or ministries, restoration of historic constructions and agricultural structures.

Table 11. Survey participants' responses regarding the most appropriate types of buildings for CLT. N=286.

Please indicate in what type of buildings you think CLT would be most appropriate as a construction system.								
Type of building	**Very appropriate**		**Somewhat appropriate**		**Not at all appropriate**		**Don't know**	
	n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Residential (single-family)	100	35.0%	121	42.3%	16	5.6%	42	14.7%
Residential (multi-family)	146	51.0%	84	29.4%	10	3.5%	41	14.3%
Commercial	72	25.2%	145	50.7%	14	4.9%	49	17.1%
Educational	68	23.8%	131	45.8%	25	8.7%	56	19.6%
Governmental	25	8.7%	113	39.5%	72	25.2%	69	24.1%
Recreational	100	35.0%	109	38.1%	19	6.6%	52	18.2%
Industrial	39	13.6%	82	28.7%	87	30.4%	70	24.5%
Transportation	34	11.9%	93	32.5%	76	26.6%	76	26.6%

Note: n=number of respondents
%=percentage of responses
Sum of percentages for each building type is not 100% because not all participants rated all items.

Willingness to adopt CLT

The third objective of this study was to determine if the population of interest would be willing to adopt CLT if it were available in the market. This information is essential to evaluate the potential market success of CLT in the U.S. Table 12 shows the participant's responses to this question.

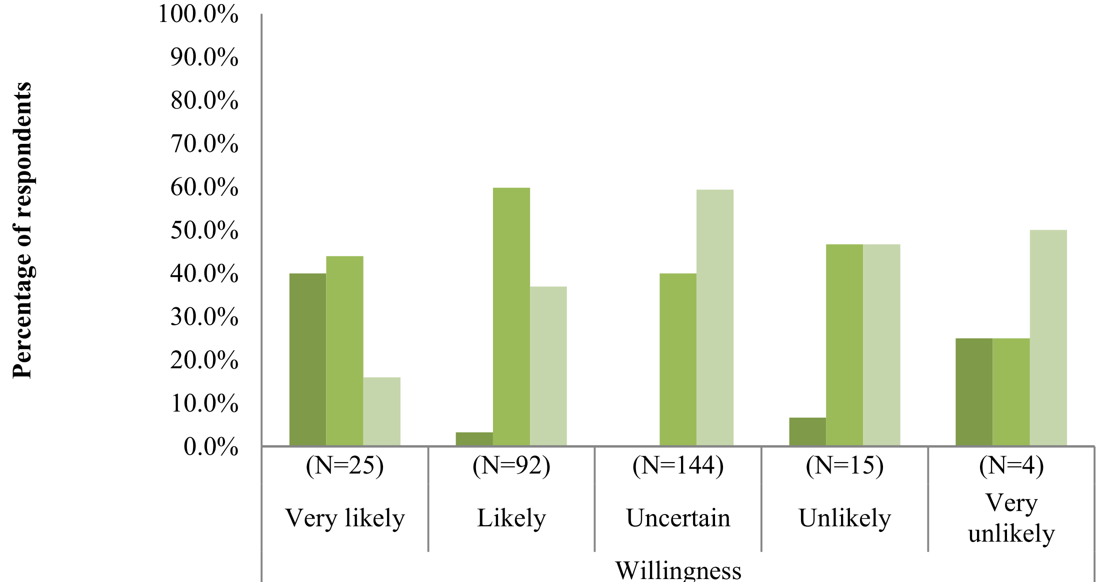
Table 12. Survey participants' responses regarding the likelihood of them adopting CLT. N=286.

If Cross-Laminated Timber (CLT) was available in the U.S., how likely are you to use CLT in one of your building projects in the near future?		
Likelihood	**n**	**%**
Very likely	25	8.7%
Likely	92	32.2%
Uncertain	145	50.7%
Unlikely	15	5.2%
Very unlikely	4	1.4%

Note: n=number of responses
%=percentage of responses
Percentages do not add to 100% because 5 participants did not answer this question.

More than half respondents (50.7%) indicated uncertainty about their likelihood to use CLT in one of their building projects if it was available in the U.S.; this finding is consistent with the level of awareness reported previously, as professionals would be hesitant to adopt a material with which they are not highly familiar. On the other hand, 40.9% of respondents answered that they would "very likely" or "likely" adopt CLT in the near future. Only 6.6% of respondents indicated that they were "unlikely" or "very unlikely" to adopt CLT in future projects.

A chi-squared test was performed to determine if there was a significant relationship between firm location and size and the likelihood of CLT adoption in the near future. The tests showed no significant relationship between these demographic characteristics and likelihood to adopt the system (location: χ^2=7.3 and p-value=0.995; size of firm: χ^2=23.8 and p-value=0.093). Chi-squared tests were also performed to identify a possible relationship between awareness and likelihood of CLT adoption. The familiarity with the system turned out to have a significant relationship with the willingness of participants to use CLT in the future. The chi-squared test for this analysis resulted in χ^2 of 84.3 and a p-value smaller than 0.001. Follow-up analysis on the relationship between level of awareness and willingness to adopt is presented in Figure 10.



	Very likely (N=25)	Likely (N=92)	Uncertain (N=144)	Unlikely (N=15)	Very unlikely (N=4)
Very Familiar	40.0%	3.3%	0.0%	6.7%	25.0%
Somewhat Familiar	44.0%	59.8%	40.0%	46.7%	25.0%
Not very familiar	16.0%	37.0%	59.3%	46.7%	50.0%

* Percentages calculated based on total respondents that answer each willingness category according to their level of awareness.

Figure 10. Percent of respondents by level of awareness and likelihood to adopt the system.

As shown in Figure 10, from all respondents that indicated to be "very likely" to adopt the system, 84% were either "very familiar" or "familiar." These results stress the importance of information and education, and also suggest that, as architects become more familiar with CLT, their willingness to adopt the system will likely grow in the country.

Likelihood to adopt CLT for high-rise buildings

Preliminary studies conducted by FPInnovations (2011) as well as the results obtained from the interviews conducted for this study (Chapter 2) indicate that CLT would be cost-competitive for high-rise buildings as a more environmentally-friendly alternative to concrete or steel structures. To assess the potential use of CLT for high-rise constructions, participants were asked about their perceptions on the likelihood of CLT adoption for buildings over six stories in the U.S. Table 13 shows the responses to this question. From all respondents, 42.0% indicated that the likelihood of CLT being used for high-rise structures was "very high" or "high;" and 28.0% of respondents said that it was "unlikely" or "very unlikely" that CLT would be used in high-rise construction. For those respondents selecting "very unlikely" to this question, a follow-up question asked participants to explain the reasons for this selection. The most commonly mentioned reasons provided were: professional liability concerns that make it hard to use new materials (meaning that architects and their insurers prefer proven construction methods), and the stringent building and fire requirements in place for high rise structures.

Table 13. Survey participants' responses regarding the likelihood to use CLT for high-rise buildings. N=286.

The current State-by-State Building Code in the U.S. limits wood construction to 5 to 6 stories. If the code changes, allowing higher buildings to be built with CLT, do you believe Cross-Laminated Timber will be used for buildings over 6-stories.		
Likelihood	**n**	**%**
Very likely	44	15.4%
Likely	76	26.6%
Uncertain	79	27.6%
Unlikely	70	24.5%
Very unlikely	10	3.5%

Note: n=number of respondents
%=percentage of responses
Percentages do not add to 100% because 7 firms did not answer this question.

A chi-squared test was performed to determine if there was a significant relationship between the level of awareness and the perceived likelihood of CLT adoption for high-rise construction in the near future. The familiarity with the system turned out to have a significant relationship with the perceived likelihood to use CLT for these type of buildings (χ^2=31.3 and p-value<0.001); meaning that as participants' familiarity with CLT increased, they tended to see high-rise building as a likely application for this construction system.

Additional comments

An open question was included at the end of the questionnaire to allow participants of the study to make comments about CLT or the survey instrument. Similar responses were coded and grouped. In total, 75 firms answered this question. Among those answering the question, 16 respondents indicated that one of the biggest concerns with the system is the lack of knowledge about the system. Raising the level of awareness and the understanding of the design principles and performance characteristics of CLT amid construction professional is thought to be paramount before any wide adoption of the system could take place. Another frequent response, mentioned by 10 participants, was related to the perceived drawbacks of the system: cost, availability in the market, and insect/fungal decay were once again mentioned as the main disadvantages of the system that may be the largest hurdles to its acceptance. Nine comments were very positive regarding the benefits of the material, especially related to its environmental and aesthetic characteristics. One respondent indicated that their firm had a client wishing to adopt CLT for a 10 story residential building, and that although the client was aware of the current barriers to the utilization of the system, he remained motivated. Another respondent mentioned that their firm was planning three CLT buildings, but no further information was provided about those undertakings. Also, four respondents indicated their high hopes for the system and requested further information.

Conclusions

The main goal of this part of the study was to assess the market potential and barriers to adoption of Cross-Laminated timber (CLT) in the United States. Specifically, this study assessed the level of awareness about CLT in the U.S. architecture community, an important group for material specification in construction projects, their perceptions about CLT, and their willingness to adopt CLT-based construction systems in the future.

For this purpose, a web-based survey was performed among U.S. architectural firms that work primarily with commercial buildings.
Results show that the level of awareness in the architecture industry is low in the U.S, since only 4.3% of 351 respondents indicated to be “very familiar” with the system. When asked about how the participants heard about CLT, a majority (42.3%) of firms indicated that they obtained the information from magazines, 20.3% from the internet and 17.5% at conferences, seminars or workshops.

Information obtained from the survey indicates that the highest ranked features of CLT are its environmental and structural performance and its aesthetic characteristics, which makes the system highly competitive against concrete or steel. On the other hand, post construction maintenance cost was one of the lowest ranked features of the product, which coincides with the common belief that wood is susceptible to deterioration due to its organic nature, and therefore requires more maintenance. Regarding the perceived barriers, respondents indicated that CLT’s availability in the market, its initial cost and compatibility issues with the building code were the largest hurdles to wide adoption of the system in the U.S. A considerable percentage of participants of this study perceived that the lack of awareness and information available about CLT were barriers to the adoption of CLT in the U.S.

For the purpose of this research, we were also interested in learning what architects perceived were the most appropriate types of building for CLT application. Respondents stated that CLT would be very appropriate for residential single-family buildings, and less adequate for industrial building. CLT was ranked highly for recreational and residential multi-family buildings, which is in accordance with the results from the interviews.

This study intended to gain insight about the willingness to adopt CLT by the population of interest. Results from the survey show that architects are uncertain about the likelihood of them adopting CLT if it were available in the market. Similarly, they were uncertain about the prospect of utilizing CLT as a construction system for high-rise building construction. Results stress the importance that information and education can have on the adoption of CLT by professionals as architects that are more knowledgeable about the system tend to be more willing to use the system.

From these results, we conclude that the future success of a CLT-based construction system in the U.S. depends in part on the information about the product reaching the target audience. The current level of awareness and some perceived disadvantages of the material make it difficult to increase the market for CLT. This diffusion of knowledge is essential in the process of getting a new product accepted by the public. It also takes time and effort to get people to trust the material. However trust can only be gained after proven success stories. In that sense it is important to make the system available in the country, so that professionals willing to try the system are not deferred by the costs of having to import the product from other regions. The experience of these early adopters will serve as the best reference for CLT.

Chapter 4

Exploring the architectural possibilities of CLT

Introduction

Results from previous phases of this study indicated that CLT could be cost-competitive for high-rise construction (over 6 stories), as an environmentally-friendly alternative to steel and concrete. Results from the survey of architects showed that architects consider CLT as an appropriate choice for multi-family, commercial, and recreational buildings. These results provided the input for the next step in the research, in which the development of one CLT building at the preliminary design level was carried out.

The goal of this component of the study is to explore and showcase the architectural possibilities of CLT, through the design of a multi-family residential building. Technical features of the system are considered more as an exploration of possibilities rather than as design constraints.

Methodology

Site selection and analysis was conducted prior to defining the design for the project. Dimensions and photographic records from the selected site were taken and used for design considerations.

Volumetric exploration for the project was assessed using basic paper models. Information about elements structural capabilities and general advice was requested from a company with plans of making and selling CLT in the U.S.

Diagrams were used to communicate basic architecture concepts developed in the project. A final set of blueprints, including floor plants, elevations, sections and construction details of particular elements were developed using computer aided design software AutoCad (Autodesk, 2014). Also, 3D images were created to illustrate the spatial possibilities that CLT allows to generate. Images were rendered in Archicad (Graphisoft, 2014) and retouched in Adobe Photoshop (Photoshop, 2014).

Preliminary design considerations

One of the first steps in the process of designing a building, independent of its nature, is the selection and analysis of the construction site (WBDG, 2014). Good site planning is important to cut construction, operation and maintenance costs shorten construction schedule and guarantee the success of the development (USGSA, n.d.). Numerous aspects are considered in the process of selecting a site:

(a) Accessibility

The site should be easily accessible in relation to the transportation, schools and shopping areas (WBDG, 2014; Canada Mortgage and Housing Corporation, n.d.). The availability of services available to the site is another important consideration that must be taken into account, as it is usually expensive to bring or upgrade water supply and sewage systems, power and other utilities, as well as roads and sidewalks, to a site (EPA, 2014). Locating a building near existing infrastructure can reduce the need of building costly systems (WBDG, 2014).

(b) Orientation

Selecting a site with good orientation is a key aspect that can help maximizes solar energy absorption in the winter and minimizes absorption in the summer. According to Reichel (2005), total energy use can be reduced by 30% to 40% in most parts of the U.S. by designing a building to the right orientation.

Building orientation can also maximize daylighting potential, which can reduce electricity requirements for lighting. The U.S. Department of Energy's Federal Energy Management Program (2007) reports that daylighting can significantly cut energy used for lighting, sometimes by 75% or 80%.

(c) Topography

The topography of the site plays an important role in the design of a building and can greatly influence the cost of the development. The shape, slope and soil conditions have an impact on the development (Canada Mortgage and Housing Corporation, n.d.). Sites with slopes can be used as an advantage for the design professional; however sites with steep slopes are usually more costly because of required infrastructure, such as complex and deep foundations, retaining walls, among other aspects.

By selecting a site that doesn't disturb natural surroundings, and by designing the site to minimize the impact on infrastructure, the delays and costs associated with the shaping of the lot can be greatly reduced (WBDG, 2014). For example, one way to reduce the amount of storm water piping is by retaining major vegetation features to the extent possible or by including porous pavement that can help promote natural infiltration of rain water (Canada Mortgage and Housing Corporation, n.d.).

(d) Architectural Program[1]

Multi-family residential building developments in the U.S. surged with the rapid rising demand for apartments during the recession (Glink, 2013). Particularly, in Minnesota one of the factors affecting the growing real estate market is the job growth and low unemployment rate (Dingman et al., 2013).

According to a report by Dingman et al. (2013), Minneapolis has been experiencing the highest rent growth and the lowest vacancy rates in a decade. More than 90% of current and projected developments are in the Minneapolis-Saint Paul metropolitan area, where the core job and amenities areas are located. In particular the areas seeing the highest number of developments are Downtown Minneapolis, Uptown Minneapolis and the University of Minnesota area (Dingman et al., 2013). Knowing the characteristics and trends of the population to be served is essential to plan the program and amenities we plan to offer.

Project Description

Location

The project will be located in Central Minneapolis, on Nicollet Island. The Island is crossed by the Hennepin Avenue Bridge that connects Downtown with Northeast

[1] In Architecture, the term "program" refers to all the proposed activities to be included in the building, which are essential for its operation (e.g. amenities)

Minneapolis (Figure 11). North from the bridge is the DeLaSalle High School and a series of multi-family residential buildings and Victorian houses.

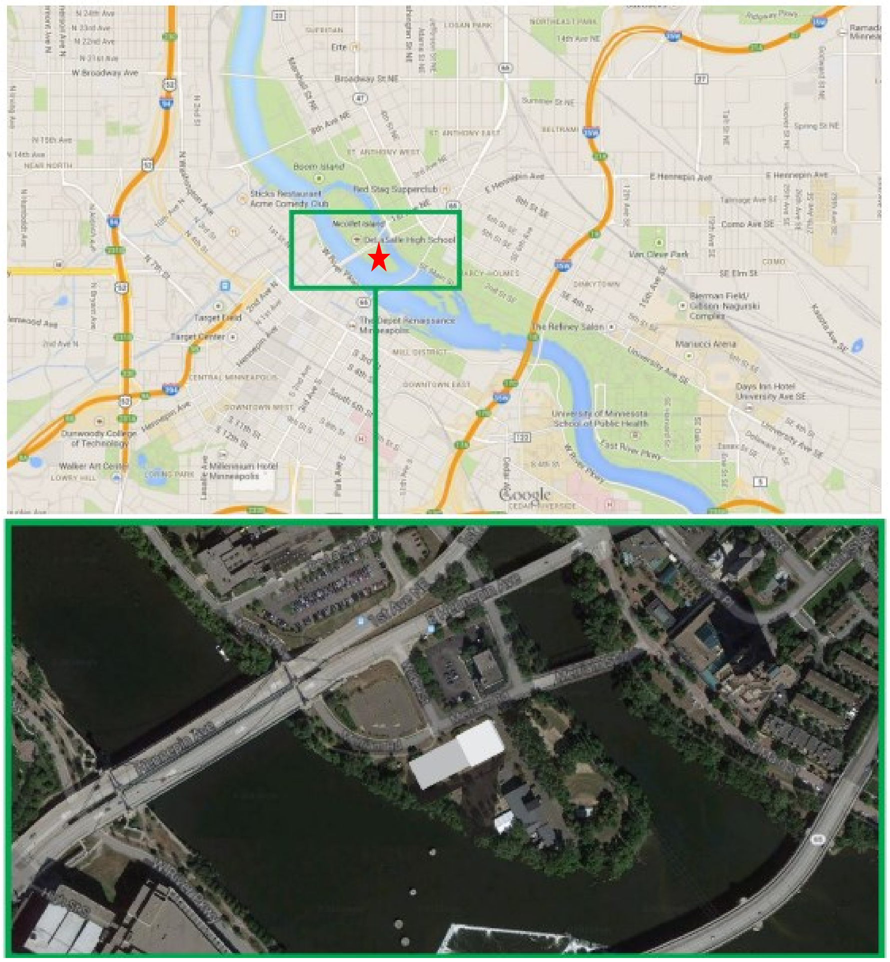


Figure 11. Location of the building. Source: Google Maps.

South from the bridge, in the corner of Merriam Street and Power Street and next to the Nicollet Island Pavilion is the site chosen for this project. On the Mississippi River bank and looking towards Downtown Minneapolis and the Saint Anthony Falls area, the site is located at a 5-minute driving distance from Downtown Minneapolis, 15 minutes on foot.

The topography of the site is characterized by a light slope and natural vegetation, which will be incorporated into the design of the building. The proximity to the river and the views towards Downtown are going to be accentuated by the design and used as a marketable value-added feature of the building.

Design concept

The idea behind the design concept lies on demonstrating the architectural and structural capabilities of CLT as a construction material. The design shows how the material can be used to solve long spans without the use of intermediate supports, the possibility to cut the panels without affecting its structural performance and demonstrates the potential use CLT for high-rise buildings. According to the results from the interviews in the first part of this research (Chapter 2), CLT has been modeled in laboratory for 15 stories buildings, however no building has ever been built over 10 stories high (e.g. Forte Building in Melbourne, Australia (Lend Lease, 2013). To push this building height boundary, it was decided to design a 15-story building.

As mentioned, the architectural program selected for this project is a multi-family residential building. This program will include a series of amenities that are usually found in these types of buildings and would help market the project and compete with existing developments in the area. The 15-story building will be organized according to the different activities included in the program, as shown in Figure 12.

Private	Apartments	3th to 16th Floor
Semi Private	Amenities TV Room Playroom Music Room Fitness Center Pool	2nd Floor
Public	Multipurpose Room Entrance Hall Exterior Space Green Area Deck	Ground Floor

Figure 12. Functional organization of the building.

Volumetrically, the project will consist of two parts: (a) a tower (apartments – Floor 3 through 16); (b) a horizontal volume (amenities – Floor 2). The articulation of both volumes will help separate public from private areas. The horizontal volume will be elevated from the ground with concrete piles, leaving the ground floor level exclusively as main access point to the building (Figure 13). The rest of the ground floor level will be an exterior, open, public place available for recreational activities. The design of the ground floor will complement and enhance the development and the neighborhood. The tower volume will be configured as the juxtaposition of single box-like volumes rotated 90 degrees from each other (Figure 14). This generates a more dynamic design and attention-grabbing architectural design.

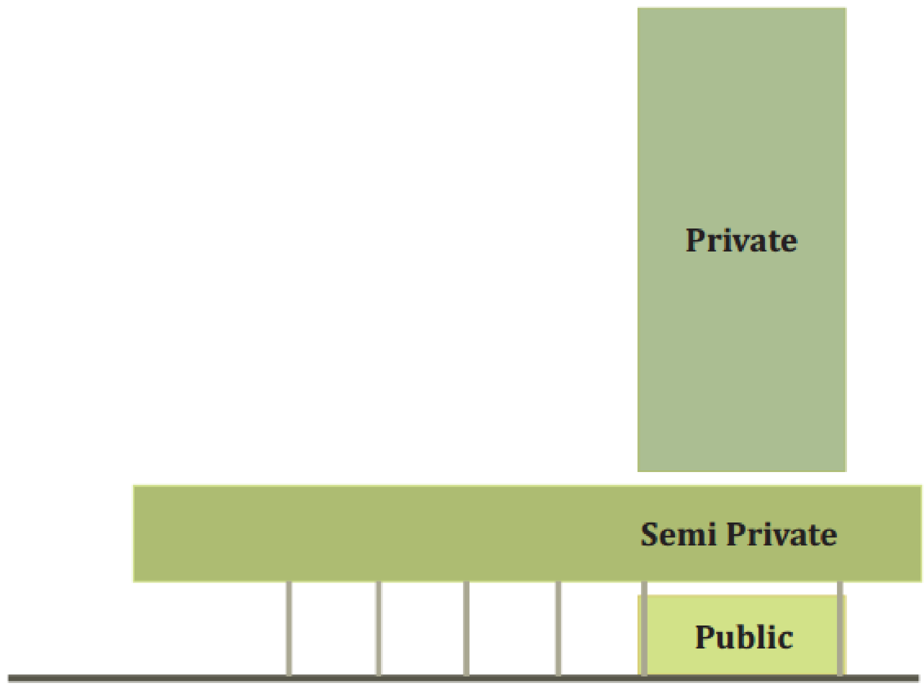


Figure 13. Volumetric organization of the building.

Existing characteristics of the site are reinforced by the design. Flowing and unblocked visuals towards the river and the city will define the design of the first two floors. The natural terrain will flow under the building untouched. The exterior will blend with the interior on the ground floor and existing vegetation will be kept in place and interact with the horizontal volume, through perforations in the slab (Figure 14). The structural piles on the ground level will then mimic and blend with the existing tress.

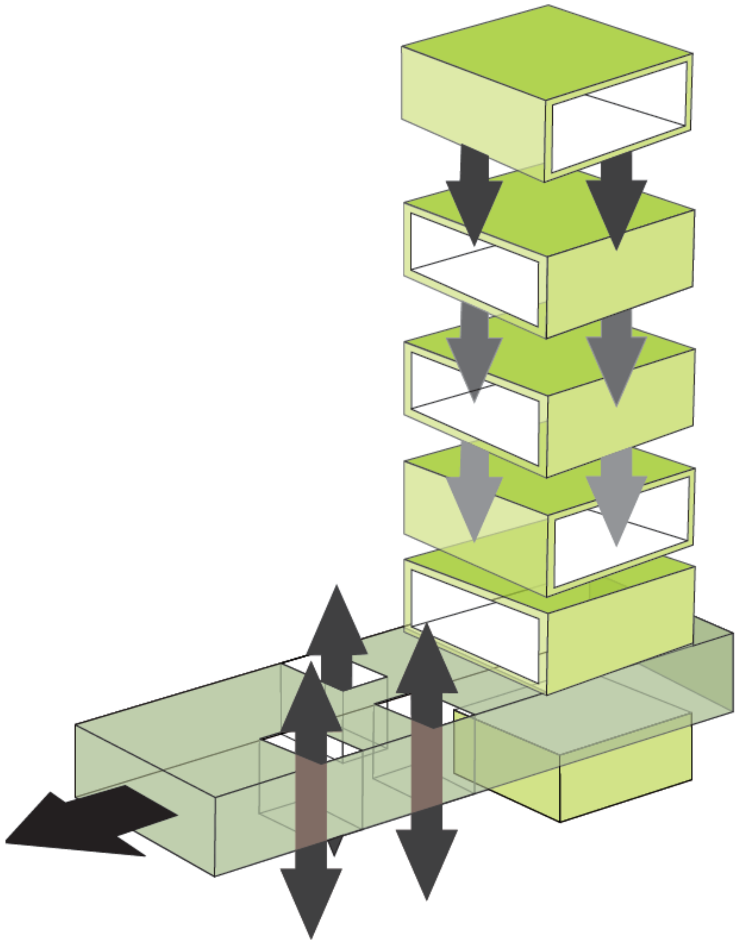


Figure 14. Volumetric configuration of the horizontal volume accentuates the connection with the exterior through perforations in the slab and the views towards the Mississippi River/Downtown area.

Materiality[2]

Although the project's main goal is to explore the possibilities of CLT, other materials were also taken into account for the design of the building. Since the site is located by the Mississippi river, a cast-in-place, shell-less type, reinforced concrete pile system was selected. Pour-on-site concrete will also be used for the retention walls in the basement, as well as the basement and ground floor stair and elevator shaft. The horizontal amenities volume is placed on concrete piles and a precast concrete slab (Figure 15). This

[2] In Architecture, the term "materiality" refers to the materials used in the construction of a building.

decision was taken to reduce the amount of piles on the ground floor and to avoid moisture problems in the swimming pool area located on the second floor.

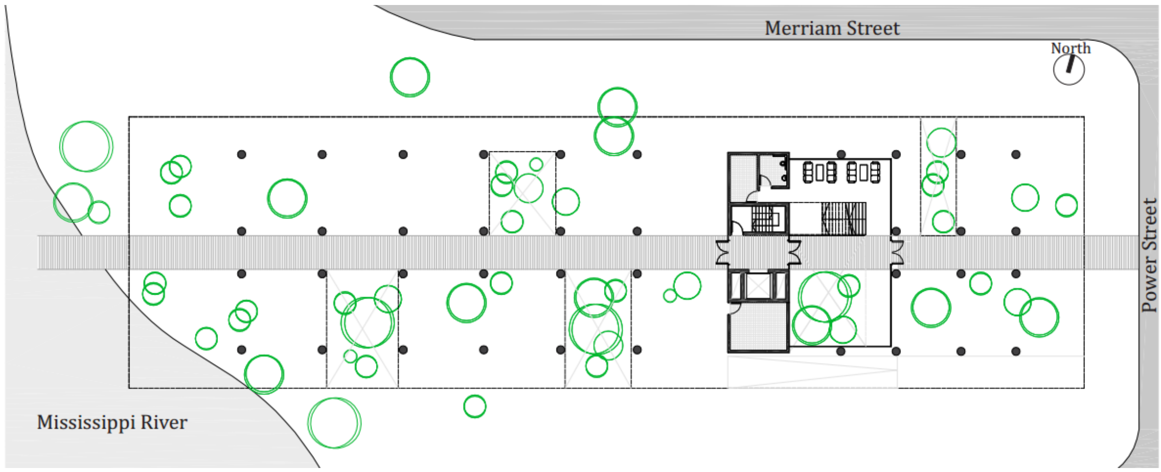


Figure 15. Structural Diagram – Ground Floor.

Over the second floor, the structure will be exclusively built of CLT elements, including the stair and elevator shaft (Figure 16). Special interest was placed in the construction details, in particular, those related to solving the union between concrete and wood, to avoid moisture related issues. Construction details are presented in the following section.

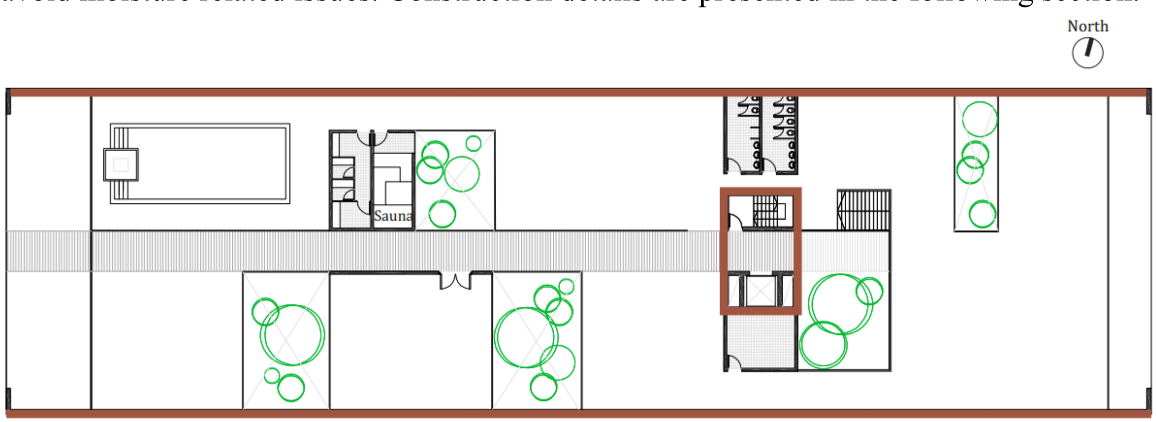


Figure 16. Structural Diagram - Second Floor. Main CLT elements are marked in brown.

CLT is going to be exposed in common areas to benefit occupants with the aesthetic characteristics of the material. However, CLT will not be left exposed in certain key places in apartments, such as bathrooms, kitchens and bedrooms. This decision was reached to maintain all electric, water and HVAC systems hidden behind the walls and above the ceiling. This makes for easier construction and allows for maintenance of the systems.

To show the structural capabilities of the material, maximum spans of up to 24.6 feet are going to be used. Also, 10 and 6 feet wide terraces without intermediate supports will be incorporated in the design. Selected lateral walls in the residential area will be perforated to incorporate floor-to-ceiling windows for the living spaces located in those areas. The intention with these openings is to show that CLT allows perforations without compromising the structural integrity of the elements (Figure 17).

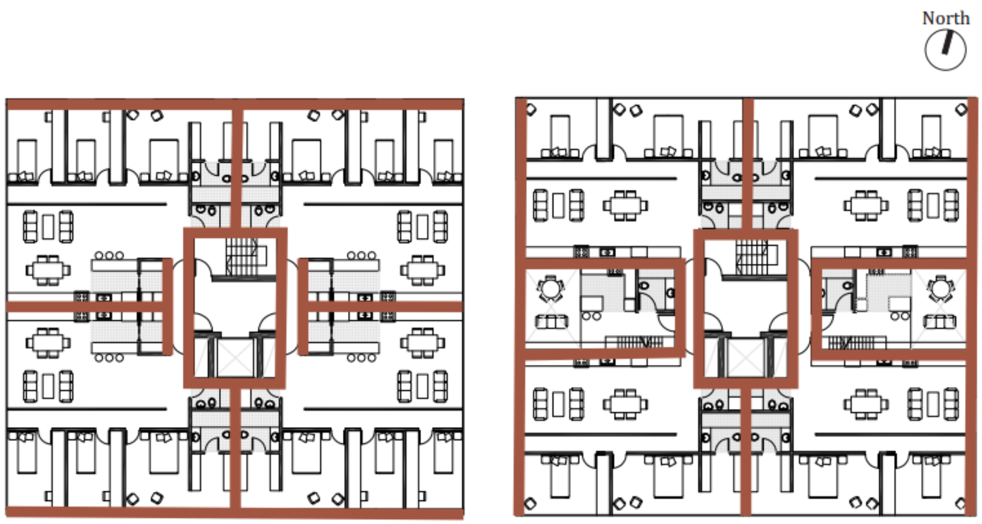


Figure 17. Structural Diagram - Apartments. Main CLT elements are marked in brown.

For the envelope, the QuadroClad Façade, a lightweight rain-screen metal façade system (Hunter Douglas, 2014) was selected. This system will not only protect the CLT against environmental agents but also help us achieve a modern, pure and austere exterior architectural language. Details of the façade are going to be developed in the following section.

Building layout

The pedestrian and vehicular accesses of the building are located on Power Street. A transparent glass box and a wooden deck mark the access to the building and visual connection of the entrance with the river. The entrance hall, interior patio and vertical circulation to the basement and upper levels are located on the ground floor. A staircase located by the entrance serves as a public access to the second floor and helps separate the access to public and private areas, thus improving the security of the building.

A secondary independent access, through which occupants of the building can access the riverfront exterior patio area, is located by the elevator. A storage area, with access from the exterior, is situated by the elevator shaft. It provides space for gardening supplies as well as exterior equipment/furniture available for occupants to use in the building premises (Figure 18).

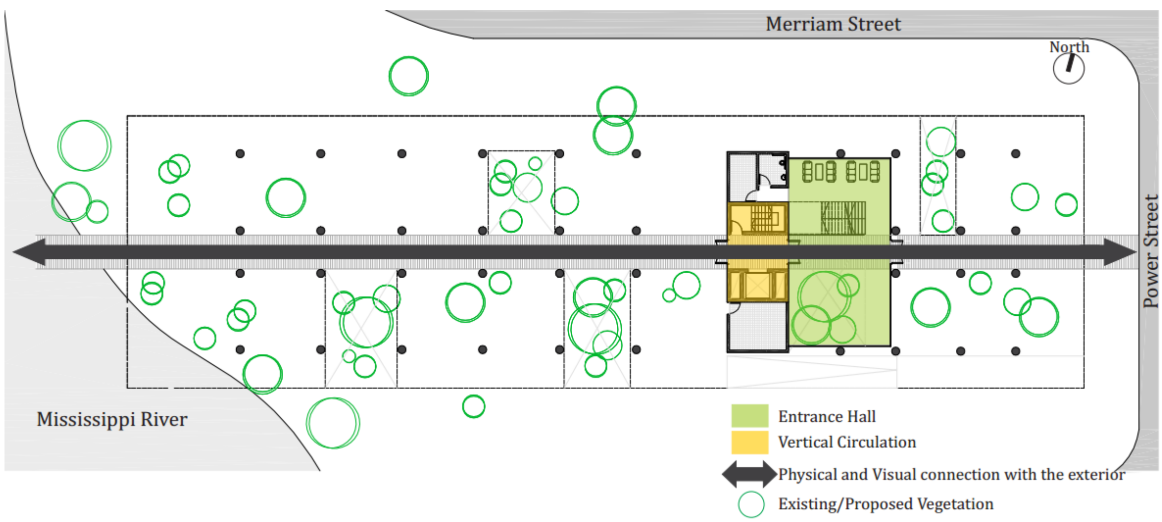


Figure 18. Ground floor diagram.

A total of 33 vehicular parking spaces and 40 bike racks are going to be located in the basement of the building. This area will be accessible from the exterior through the ramp or from the entrance hall located in the ground floor through the elevator/stairs (

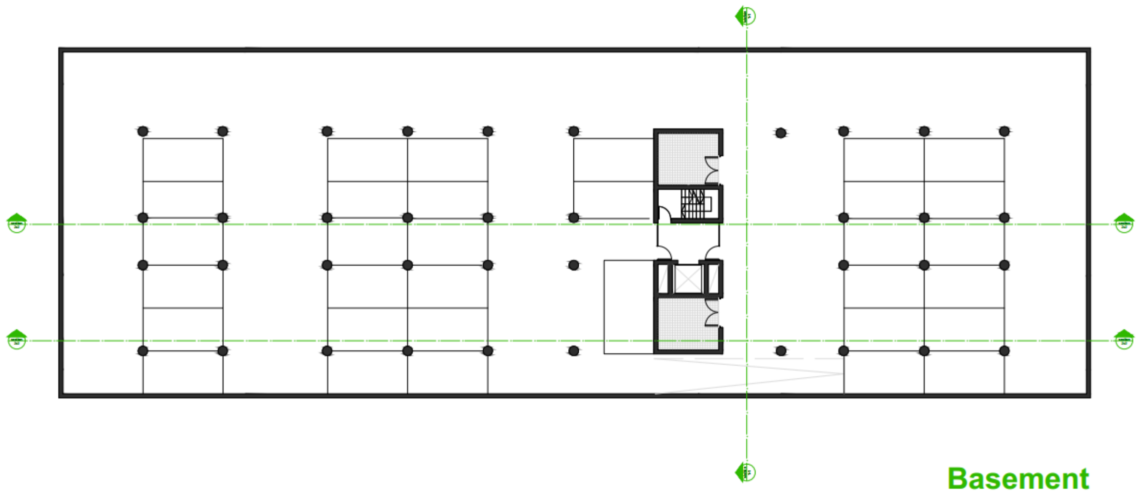


Figure 23).

Public areas and amenities of the building are located on the second floor. From the entrance hall on the ground floor, the public can directly access a multipurpose room and terrace with views towards Northeast Minneapolis. A kitchen, storage and public toilet area are located adjacent to this room for easy use during special events. The space could either be used by occupants of the residence building or could be rented to external parties. A door would help maintain this multipurpose area separate from those private to the residents.

Towards the west side of the volume are located the amenities of the building, which include a TV room, fitness center, music room, play room, sauna, dressing-room and swimming pool. Both the swimming pool and play room are located in the furthest west end of the volume and have access to an open terrace with views towards Downtown Minneapolis and the Mississippi River. The floor and roof on this level are perforated in various parts to allow natural light to be filtered into the interior spaces. Preexisting vegetation on the ground floor will also make an appearance through these openings, serving as natural privacy screens to the areas. All spaces will be structured and connected through a central wooden deck corridor similar to the one on the ground floor (Figure 19).

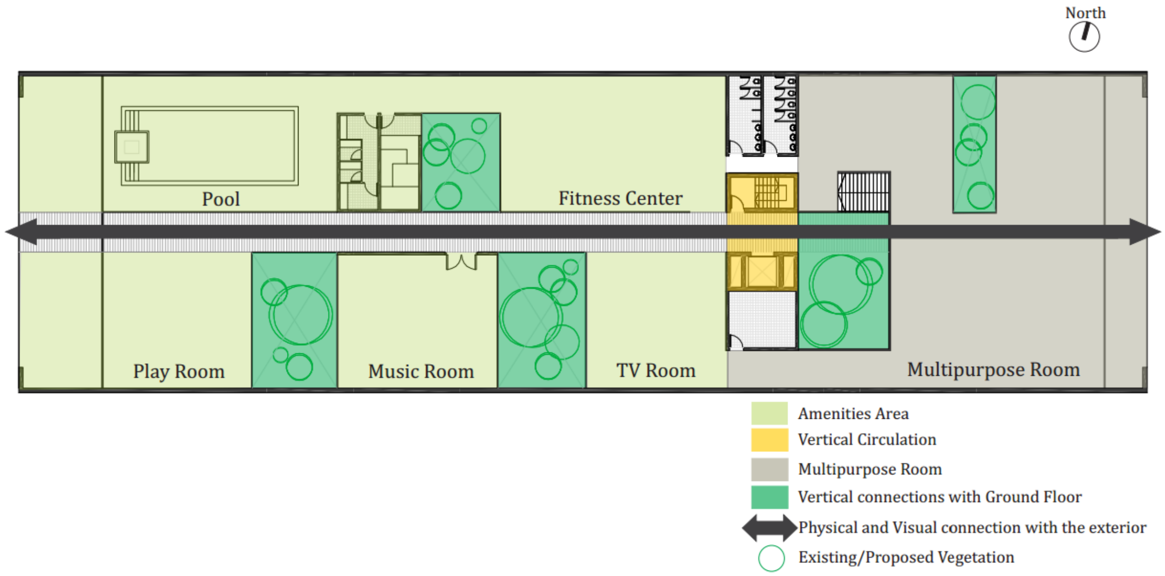


Figure 19. Second floor diagram.

A total of 68 apartments are included in the design. Apartment's types and square footage are summarized in
Table 14.

Table 14. Apartments types and square footage.

Code	Type of Unit	Area (sqft)	Number of Units	Total Area (sqft)
A1	2 Bedroom + 2 Bathrooms	1,313	32	42,022
A2	3 Bedroom + 2 Bathrooms	1,560	24	37,440
A3	Studio	419	8	3,352
A4	Loft	678	4	2,712
TOTAL			**68**	**85,526**

The 14-story residential area is going to be connected to the rest of the building through a central elevator/staircase shaft; made completely out of CLT, it will serve as the structural core of the building. A foyer on each floor will serve as access to each apartment.

To maintain a clear, consistent and functional layout throughout the building, service areas (bathroom, kitchen, laundry room) will be located strategically, and overlapping on each floor, towards the core of the building (Figure 20).

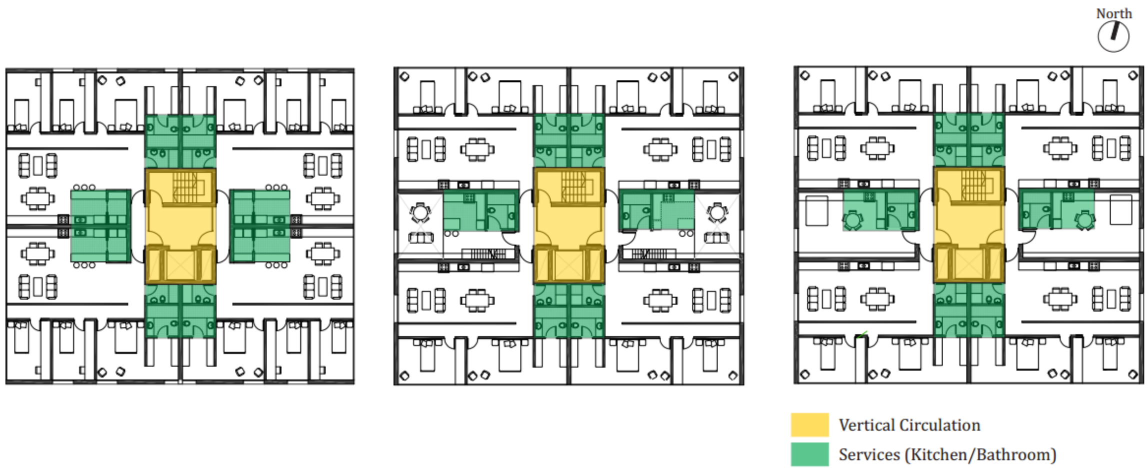


Figure 20. Functional organization of apartments.

Main floor plans, elevations, sections and images can be found in the following section. Additional floor plans can be found in the Appendix 4.

Construction details

As with any wood structure, it is critical to pay special attention to the construction details, since good design is the key factor that guarantees long-term durability and performance of the enclosure. Moisture problems are one of the most challenging issues that could affect wood's durability, leading to mold and decay. Properly designed construction details can prevent moisture issues to affecting the structure. Construction details can also help avoid issues related to the thermal performance of the envelope, such as thermal bridging, air-tightness, and acoustic and vibration performance of CLT slabs.

For the proposed CLT building presented in this chapter, six construction details were generated. Those referring to the solution of the envelop include details from the light-weight rain screen façade system from Hunter Douglas (Hunter Douglas, 2014), the continuous rigid insulation solution to guarantee a correct thermal performance of the envelope and the air-water barrier attached to the CLT panels to guarantee air-tightness and protect the wood from any moisture coming from the exterior (Figure 29, Figure 31, Figure 34, Figure 35). The details of the envelope were generated based on the information provided by the manufacturer of the façade system (Hunter Douglas, 2014), the CLT Handbook (FPInnovation, 2013), and the Builder's Guide to Cold Climates (Lstiburek, 2006).

The interior details show the solution for partition walls and slabs and include all the layers necessary to assure a correct acoustic and vibration performance of the building (Figure 31, Figure 32). These details were generated based on the information presented in the CLT Handbook (FPInnovations, 2013). All construction details can be found in the following section.

Project drawings

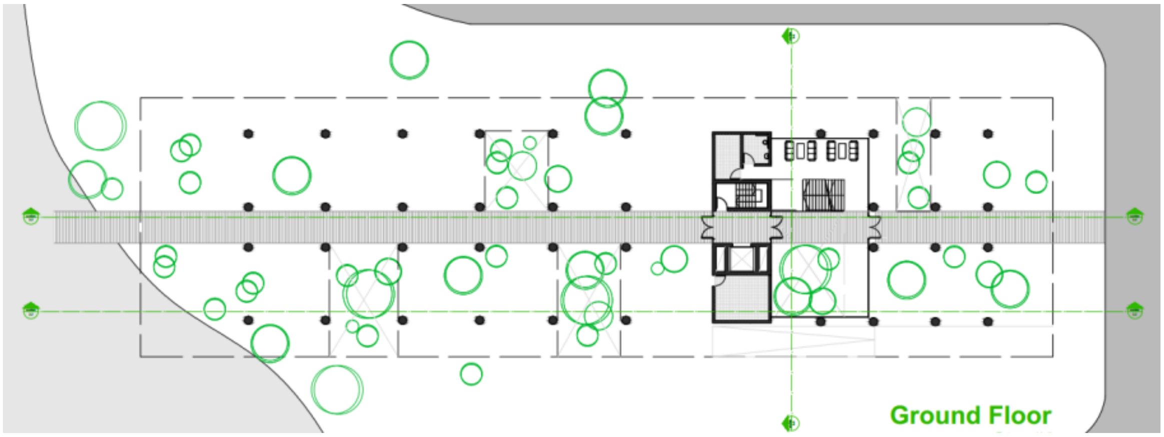


Figure 22. Layout of the Ground floor showing the entrance to the building and the exterior space.

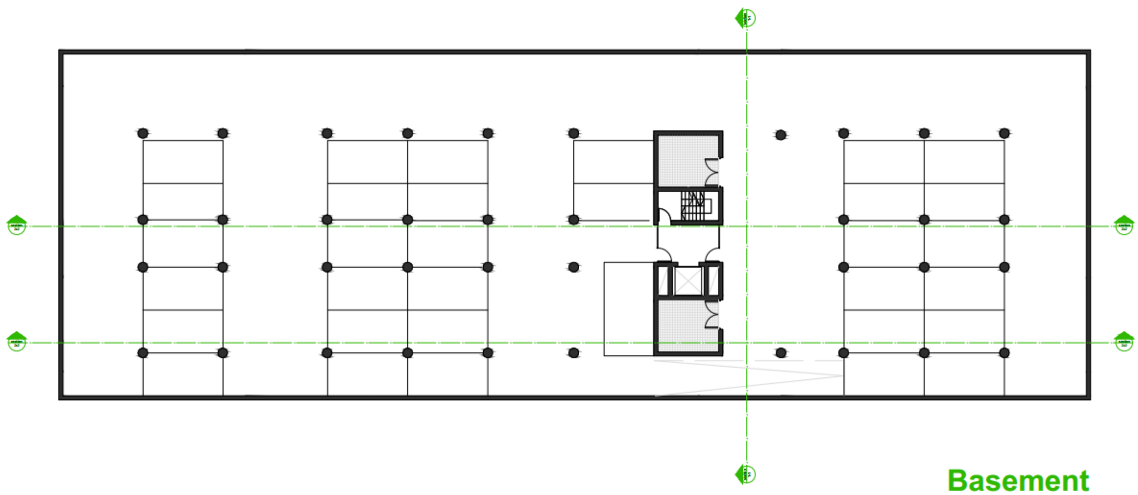


Figure 23. Layout of the Basement floor.

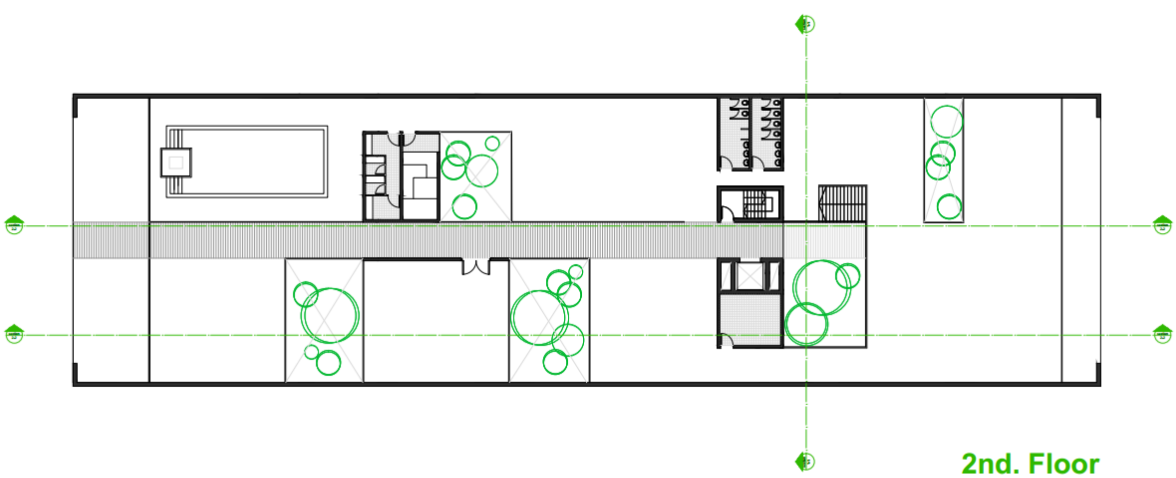


Figure 21. Layout of the Second Floor, where all amenities are located.

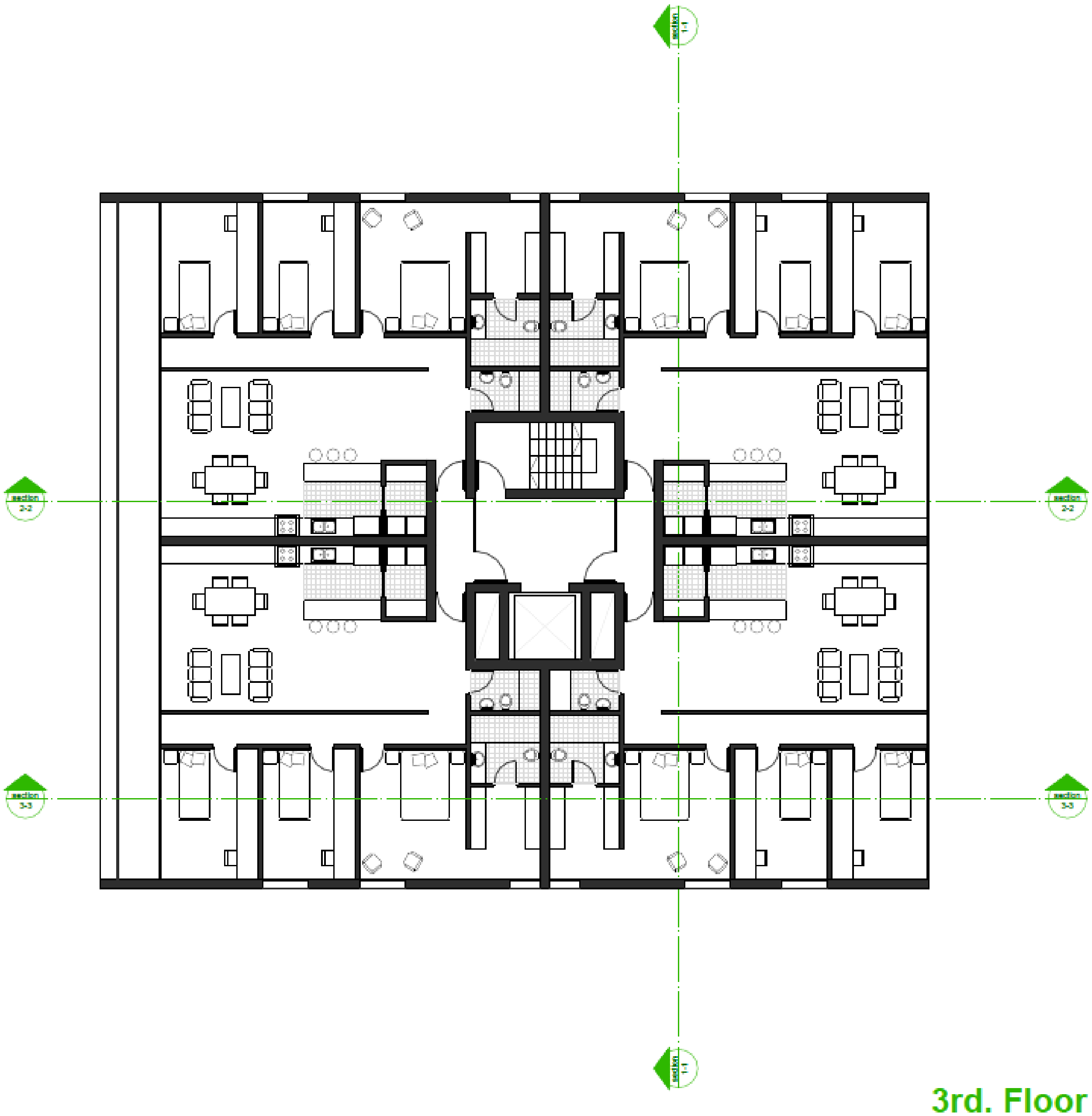


Figure 24. Example of a typical apartment floor layout (for the rest of the floor plans see Appendix 4).

Figure 25. Transverse section.

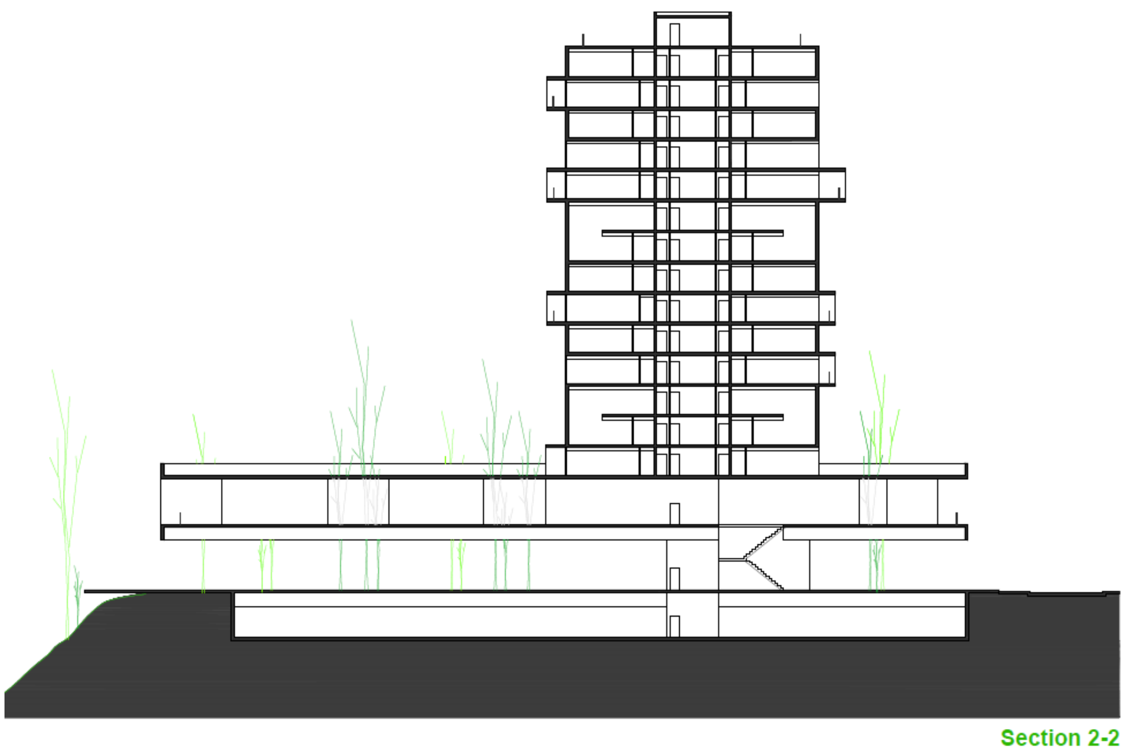


Figure 26. Longitudinal section.

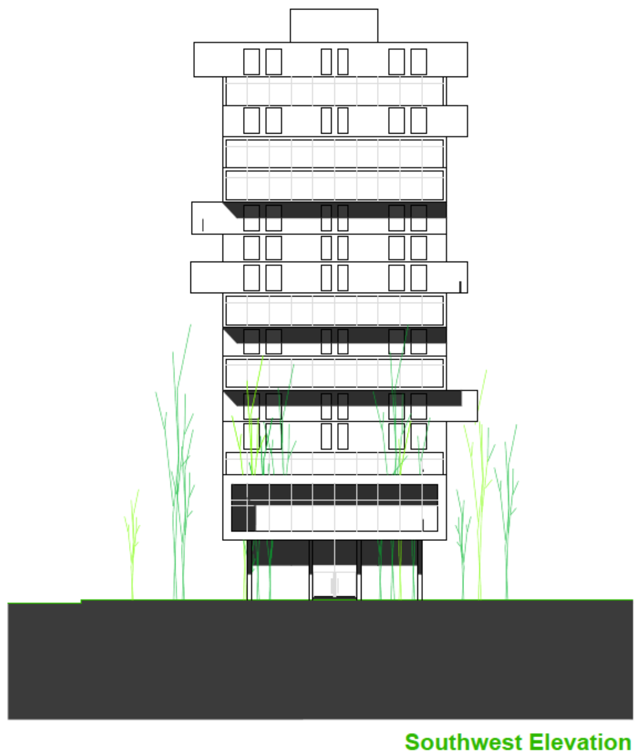


Figure 27. Southwest elevation.

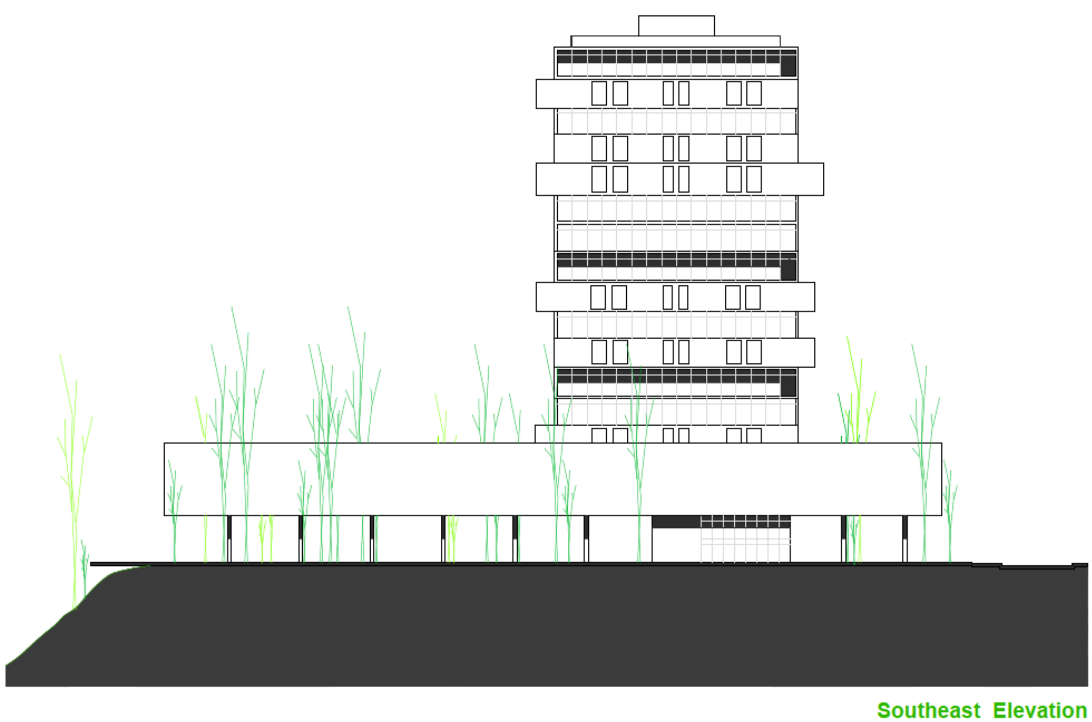


Figure 28. Southeast elevation.

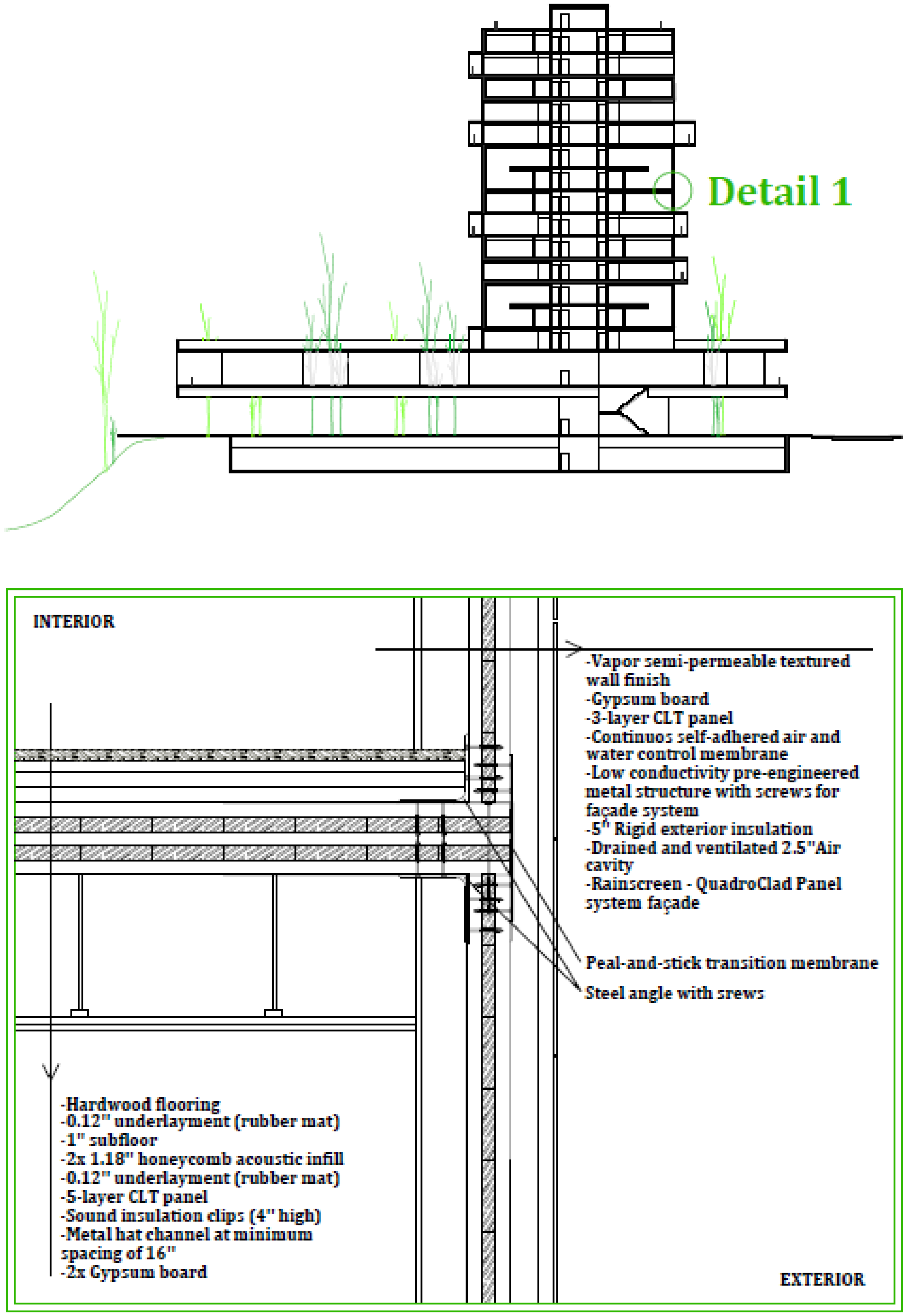


Figure 29. Façade detail, showing the layers used to solve the envelope and the interior floor/ceiling.

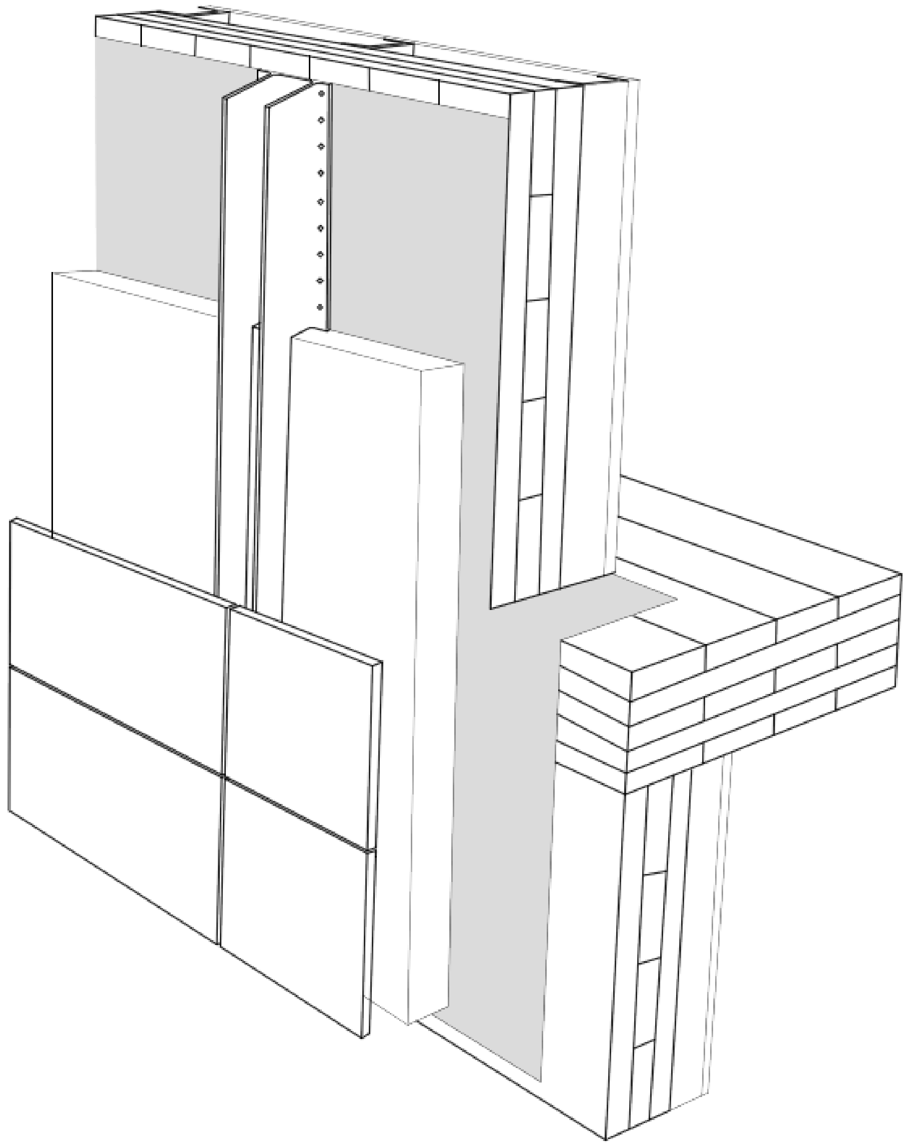
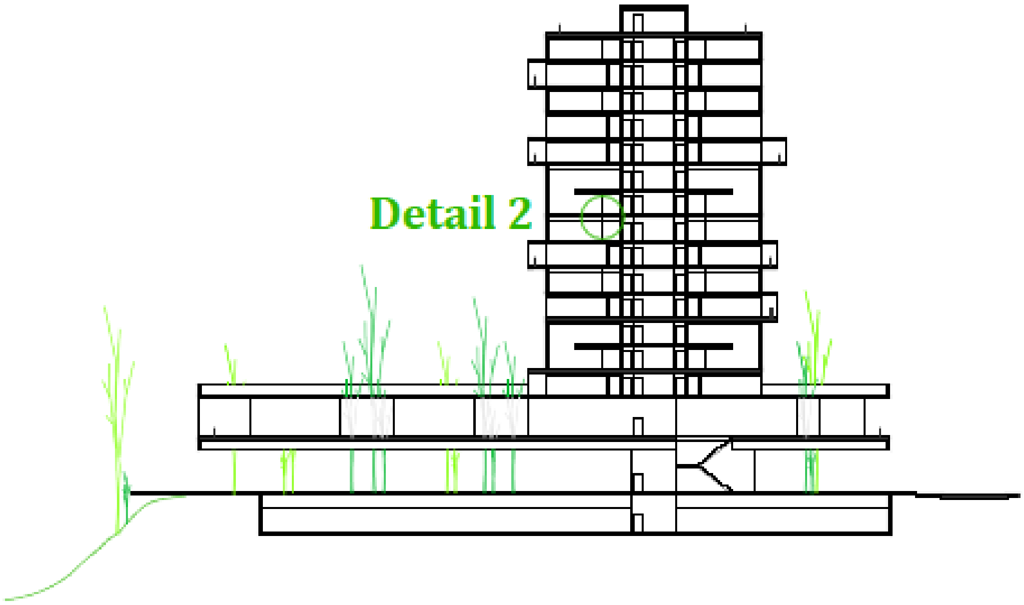


Figure 30. Three-dimensional diagram of the façade system.



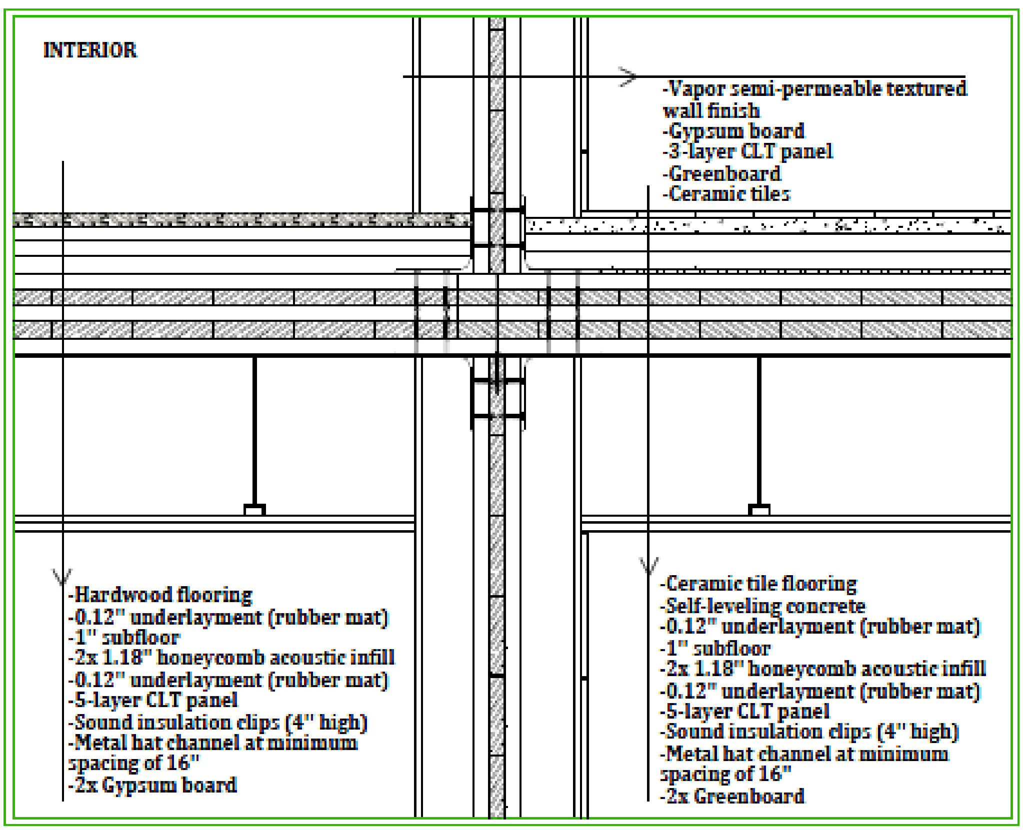
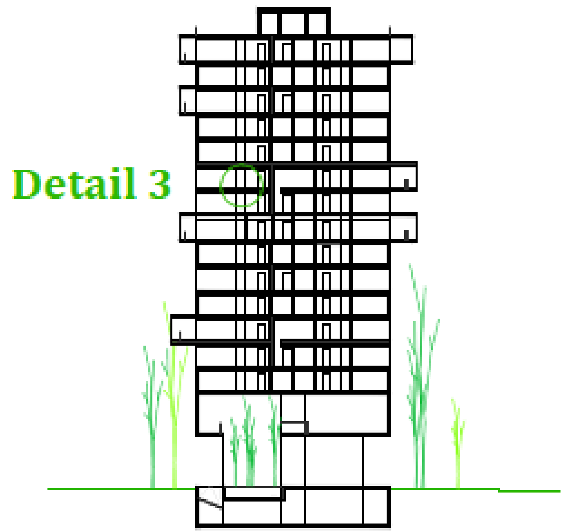


Figure 31. Detail for the floor-ceiling-wall solution for rooms and bathrooms.



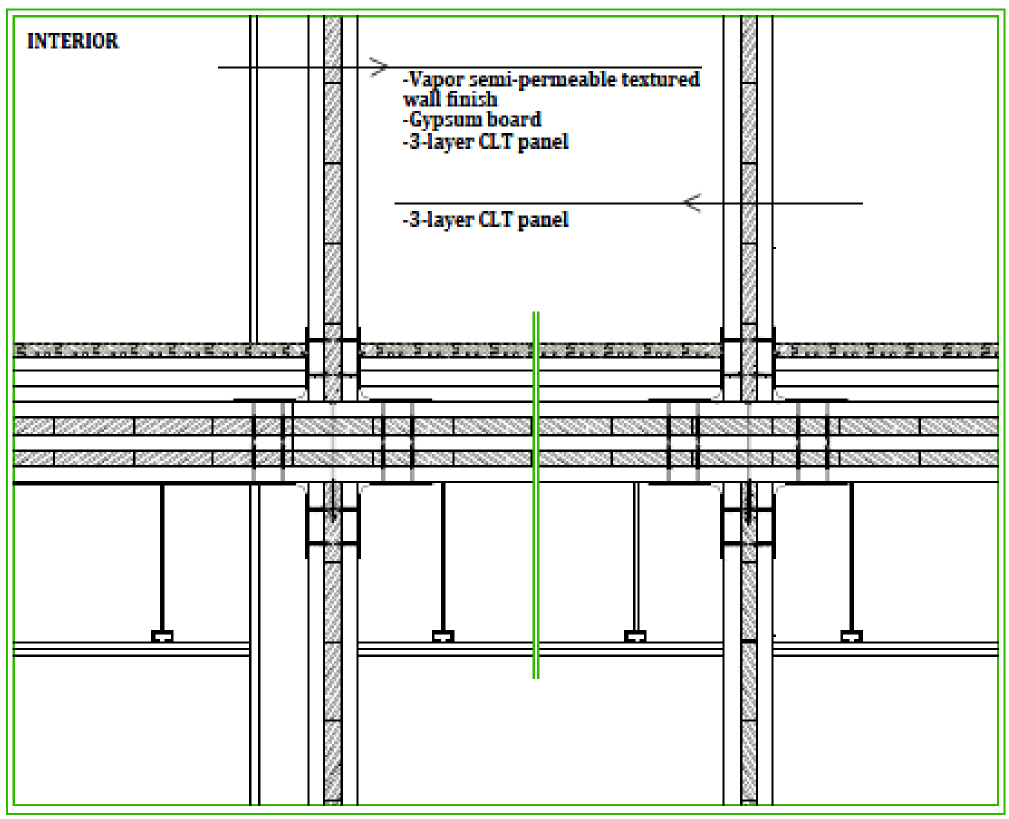
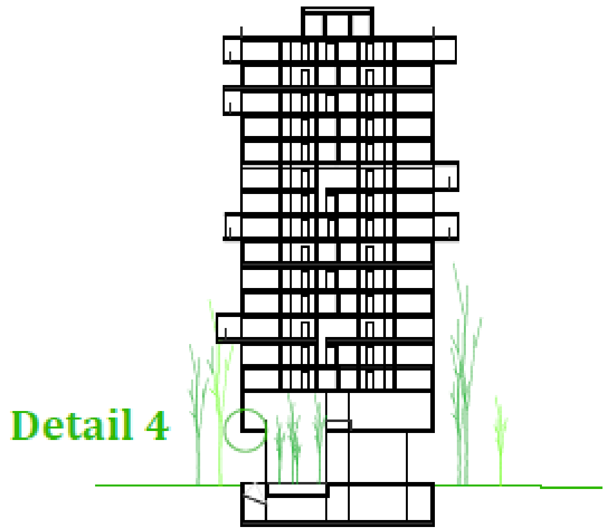


Figure 32. Detail for the floor-ceiling-wall solution with exposed CLT panels.



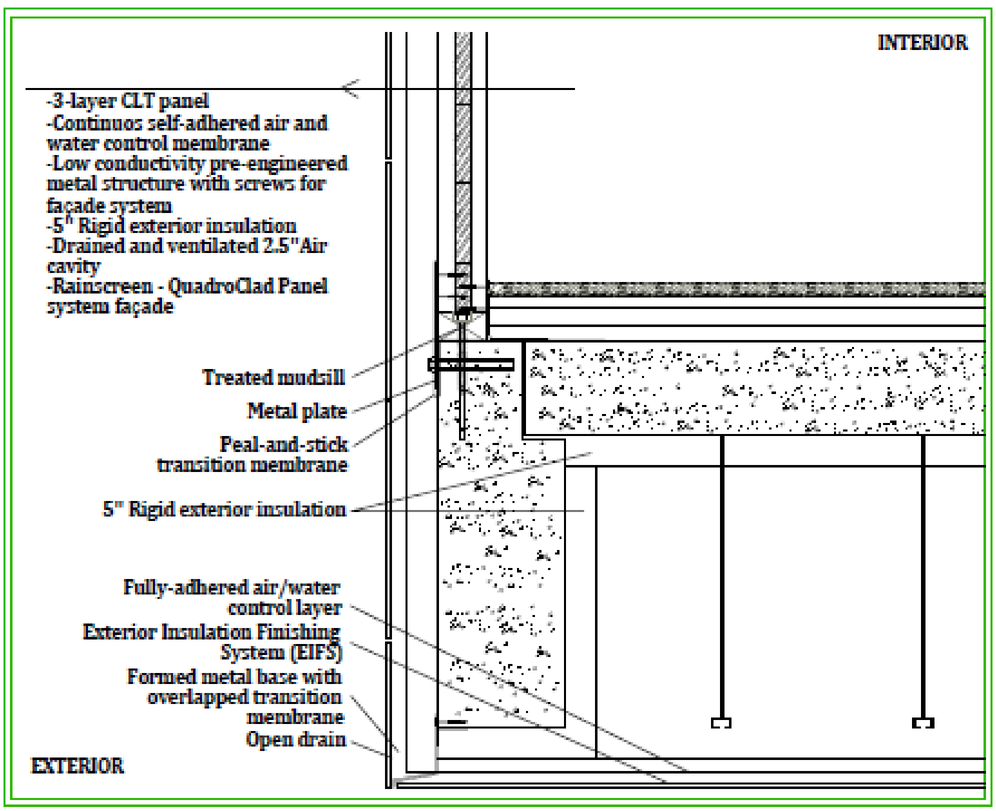
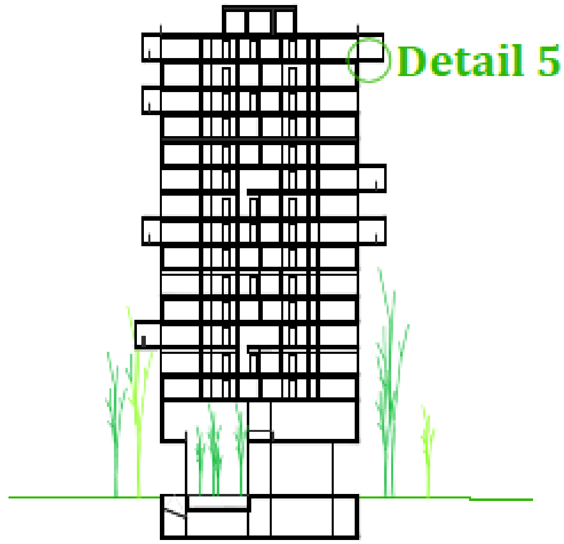


Figure 33. Detail for the concrete-wood connection solution.



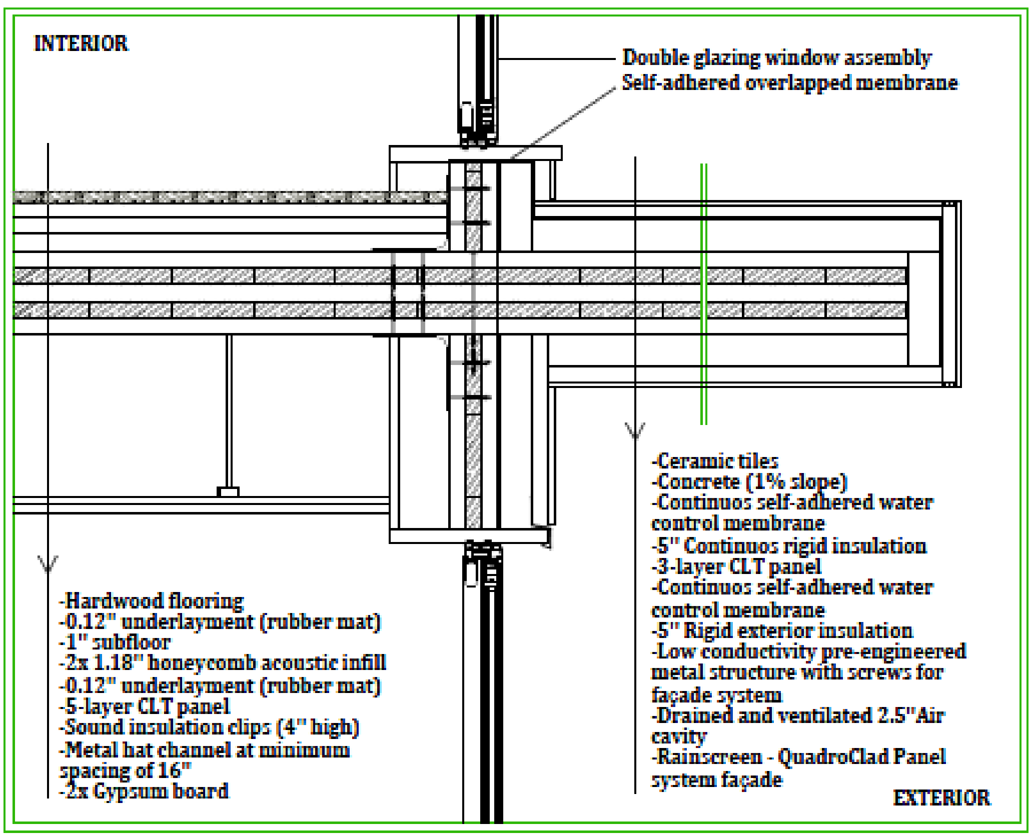
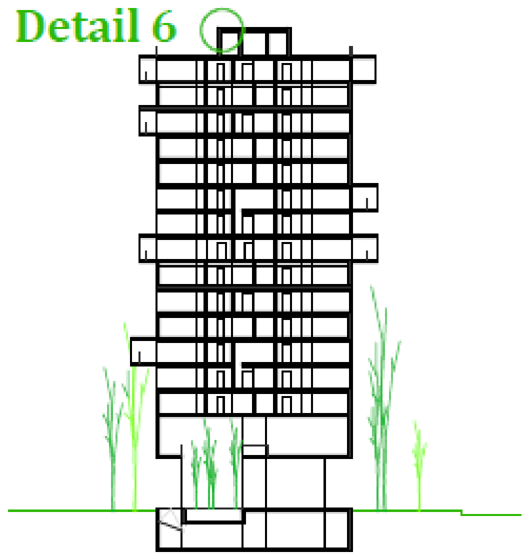


Figure 34. Detail of the terrace solution.



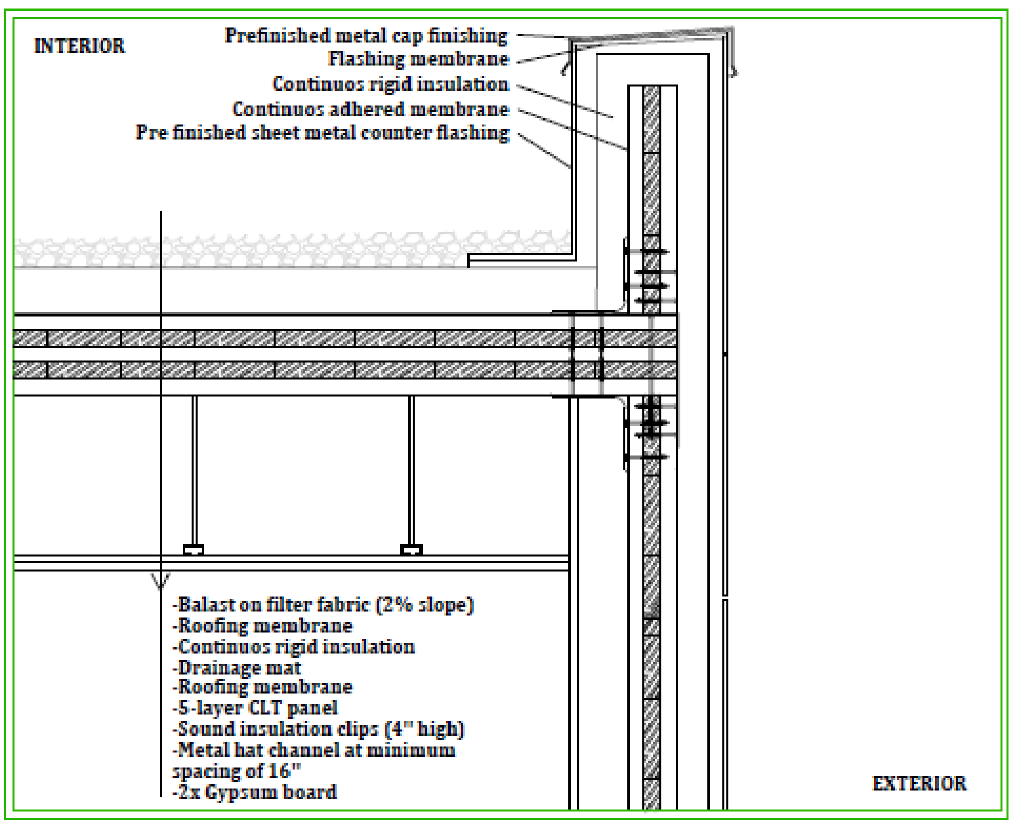


Figure 35. Detail for the roof solution.

Figure 36. Main entrance.

Figure 37. Second Floor. View of the amenities area.

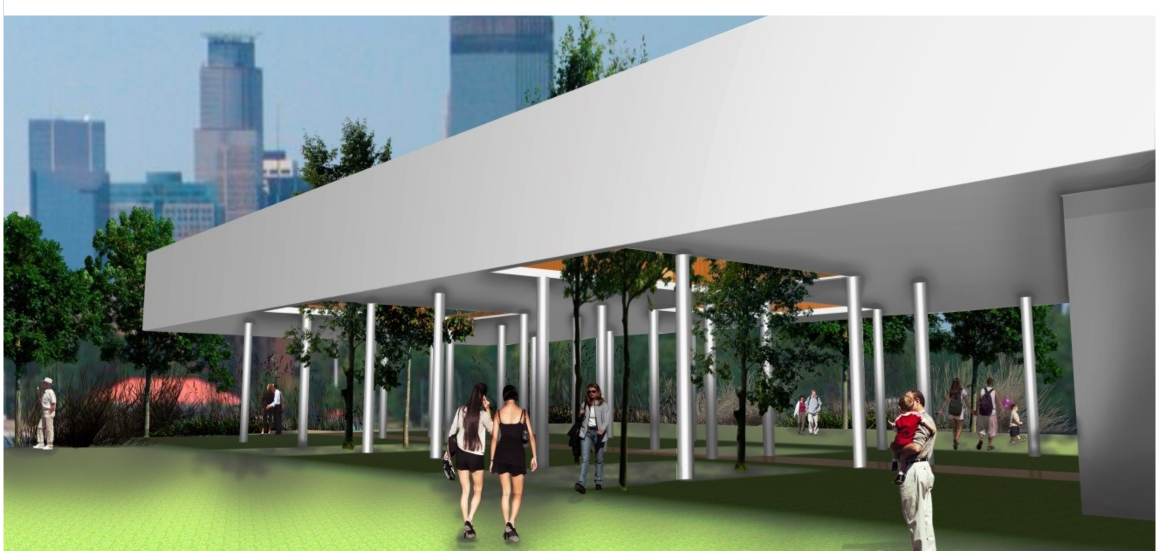


Figure 38. Exterior view.

Conclusions

The objective of this study was to explore the architectural possibilities of CLT in a multi-family residential project, which according to previous studies is being perceived as one of the most likely future uses of CLT in the U.S.

By maximizing the spans of CLT elements used for slabs and roofs, the designer achieved opened and fluid living spaces. CLT also enables the design of wide terraces, which typically would not have been able to be designed without intermediate supports and beams. The cross-laminated nature of the panels enabled the designer to plan openings on outside walls without compromising the structural integrity of the structural elements.

The enclosure was also defined with a minimum amount of elements (unlike a wood-frame construction system), which allowed the construction of a much tighter, and therefore energy efficient, envelope. This would directly translate into less heating and cooling loads requirements year-round. Due to the massive nature of CLT, less insulation was required to achieve a high thermal resistant enclosure assembly.

This project is only one of infinite possible solutions for a CLT-based multi-family residential building. Since this project is only intended to be a preliminary design, further research should be conducted to validate the structural performance of this design. Time and cost of construction comparisons could also be performed to complement this study.

Chapter 5
Conclusions

The main goal of this research was to assess the market potential and barriers to the adoption of Cross-Laminated Timber (CLT) in the United States. Specifically, this study assessed the level of awareness about CLT in the U.S. architecture community, their perceptions about CLT, and their willingness to adopt CLT-based construction systems in the future. The architectural possibilities of CLT were also explored through the design of a multi-family residential building. In this chapter, the most important conclusions from each component of the research project are presented.

Interviews with CLT experts

CLT experts interviewed for this study indicated that the main benefits of CLT-based systems come from using a natural, renewable resource (wood) as opposed to energy-intensive and non-renewable materials like concrete or steel. Another important benefit of CLT-based systems over traditional construction systems is the shorter construction time needed since CLT is a prefabricated system, in which panels come to the construction site ready to be installed. Consequently, CLT-based systems reduce labor, time, on-site waste, the occurrence of accidents and disturbances to the site's surroundings; all of which have a positive impact on the construction costs. Structurally, CLT offers a performance comparable with concrete or steel, at a fraction of the weight. CLT's layered nature provides the panels with good rigidity, stability, and mechanical properties, allowing CLT to be used for the most diverse applications (walls, floors, roofs, elevator/stairways shafts, among others).

According to experts, CLT has technical drawbacks such as its acoustic and vibration performance. Another concern mentioned was the volume of wood utilized in the manufacture of CLT panels. According to one expert, CLT panels use up to three times more wood than a wood-frame building system solution.

Regarding the level of awareness about CLT among architecture professionals, there was almost general agreement among respondents that the awareness is still low in the U.S. Reasons suggested include the novelty of the system and regional variances, meaning professionals working and living in areas with a longer tradition of wood-based construction appear to be more likely to be familiar with CLT-based systems.

The main barriers to adoption CLT systems in the U.S. mentioned by experts interviewed were Building Code compatibility, availability of CLT in the national market and perceived disadvantages of wood as a building material. In particular, the current lack of CLT manufacturing plants in the U.S. is seen as a large barrier, which adds to the construction costs, since panels need to be imported from Europe or Canada. Other barriers indicated by experts focused on the perceptions that the public may have of CLT construction systems, since they use large amounts of wood.

Responses about cost-competitiveness indicate that CLT could be cost-competitive when compared to more traditional building materials such as concrete, especially for buildings over six stories high. This is in part due to the dramatically reduced on-site construction time needed for CLT structures. Most experts agreed that CLT is cost-competitive for high-rise commercial or multi-family residential buildings, and low-rise commercial and industrial buildings, where a wood-frame system cannot be used. There was common agreement among experts in that the system would not be cost-competitive for applications where light wood-frame construction is commonly used, such as in single and multi-family low-rise buildings.

Experts indicated that the future of CLT is promising and that the adoption of the system nationwide is possible and will likely happen. It was suggested that raising the level of awareness among building professionals will be the first step towards a wide adoption of the system in the U.S.

Nationwide survey of the U.S. architecture community

The information obtained from the survey of U.S. architecture firms helps to understand the perceptions and awareness about CLT by an important group for material specification. Results show that the level of awareness in the U.S. architecture community is low since only 4.3% of 351 respondents indicated to be “very familiar” with CLT systems. Participants who reported knowing about CLT learned about it from magazines, internet, and at conferences, seminars or workshops. These results show that there is opportunity for educating the architecture community on this construction technology.

Results from the survey also indicate that structural performance, durability, aesthetics, and availability are considered the most important features when selecting a construction material (the combined percentage of respondents answering “very important” or “important” to this question were, respectively, 98.6%, 97.8%, 94.0%, and 90.0%).

Architects’ were asked to rate CLT’s performance on several dimensions according to their perceptions. The features where CLT was rated the highest were environmental performance (rated as “excellent” or “good” by 67.1% of respondents), its structural performance (22.7% graded CLT’s structural performance as “excellent” and 45.8% as “good”), and its aesthetic characteristics (ranked as “excellent” by 19.9% of respondents and “good” by 42.3%). However, post construction maintenance cost was one of the lowest ranked features of the product (26.9% of respondents graded CLT’s maintenance costs as “excellent” or “good”), which coincides with the common belief that wood is susceptible to deterioration due to its organic nature, and therefore requires more maintenance.

The main perceived barriers for CLT adoption were its availability in the market (rated by 37.8% of respondents as a large barrier), its compatibility issues with the Building Code (26.2%) and initial cost (23.1%). A high percentage of participants (56.6%) also saw the lack of awareness and information available about the CLT as key factors in the slow adoption of this product by the U.S. market. When asked about the most appropriate types of building for CLT application, 51.0% respondents indicated that CLT would be “very appropriate” for residential multi-family buildings. CLT was also rated highly for recreational and residential multi-family buildings, which is in accordance with the results from the interviews with the experts. The survey also intended to gain insight about the willingness to adopt CLT by the population of interest. Results from the survey show that architects seem divided about the likelihood of them adopting CLT if it were available in the market, with 50.7% of participants responding to be “uncertain” about the likelihood of them using the system in the future. Respondents seem less divided on their perception on whether the system would likely be used for high-rise structures; 42.0% rated this likelihood as “very high” and “high,” however 28.0% of respondents said that it was “unlikely” or “very unlikely” that they would use CLT in high-rise construction.

Exploring the architectural possibilities of CLT

The fourth and last section of this manuscript aimed at exploring the architectural potential of CLT in a specific project. The structural capabilities of the material were seen as starting point for the design of the building. By maximizing the spans of CLT elements used for slabs and roofs, designers achieved opened and fluid living spaces.

CLT also enables the design of wide terraces. The cross-laminated nature of the panels enabled the designer to planned openings on outside walls without compromising the structural integrity of the structural elements.

Final remarks

Findings from this study stress the importance that information and education will have on CLT adoption levels by architects. We conclude that the future success of a CLT-based construction system in the U.S. depends on information reaching the target audience. The current level of awareness and existing perceptions about the material may make it difficult to create a market for CLT. The diffusion of knowledge is essential in the process of public acceptance of any new product, as it takes time and effort to get people to trust a new construction system. However trust can only be gained with proven success stories. In that sense it is important to make the system available in the country, so that professionals willing to try the system are not discouraged by the costs of having to import the product. The experience of these early adopters will serve as the best reference for those considering CLT.

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Appendix

Appendix 1

Interview Questionnaire

1. Briefly describe your experience with CLT.
2. What do you think are the main environmental benefits of using CLT?
3. What do you believe are the most important structural benefits?
4. What do you think are the main economic benefits of choosing CLT?
5. What are in your opinion the main disadvantages in of the system, regarding the environmental, structural and economic characteristics?
6. What would you say is the level of awareness of the AEC Community about CLT in the U.S.? Is it high, intermediate or low?
7. What are the main barriers to implementing this system in the U.S., specifically when it comes to its environmental, structural and economic characteristics?
8. Do you think that CLT is cost-competitive with other construction systems, taking into consideration its benefits?
9. If there is a low level of awareness: What do you think are the main reasons for that?
10. How do you think people perceive the environmental performance of CLT and why?
11. How do you think people perceive the structural performance of CLT?
12. How do you think people perceive the cost? Why?
13. For what kind of buildings do you believe CLT would be most suitable in the U.S.?
14. Do you believe that CLT could be widely adopted as a construction technology in the U.S.?
15. Any other comments you might want to add about the future of CLT in the U.S.?

Appendix 2

Survey Questionnaire

Welcome to the "Awareness, Perceptions and Willingness to Adopt Cross-Laminated Timber in the U.S." Survey

Master's Degree Thesis Project

The objective of this study is to assess the market potential for cross-laminated timber (CLT) in the United States. For this purpose, this study will assess the awareness, perceptions, and willingness to adopt CLT by U.S. architecture firms. Your firm has been selected because it is part of the population of interest for this study, consisting of the main specifiers of materials in the construction industry. Participation in this survey is voluntary. However, for this research to be successful, it is very important that we receive your input. Your answers to these questions will be kept strictly confidential and no company information will be disclosed. Results will be reported in aggregate manner.

Completing this survey will take approximately 10 minutes. You could receive a report of the results from this nation-wide survey. Should you have any questions, please contact me at lagua006@umn.edu; or my supervisor Omar Espinoza, at espinoza@umn.edu. The time invested in helping us is greatly appreciated.

Sincerely,
Maria Fernanda Laguarda Mallo
Graduate Research Assistant
Bioproducts and Biosystems Engineering Department
College of Food, Agricultural and Natural Resource Sciences
University of Minnesota
320 Kaufert Lab
2004 Folwell Ave
St Paul, MN 55108

Instructions

Please read every question carefully and answer to the best of your ability. Please, do not leave any questions unanswered.

Thank you for your cooperation!

Company Demographic Information

1. In which of the following regions does your firm operate? Check more than one region, if appropriate.

- ☐ Northeast
- ☐ South
- ☐ Midwest
- ☐ West
- ☐ Alaska
- ☐ Hawaii

2. Which of the following firm size categories best describes your firm?

- 1 to 4 employees
- 5 to 9 employees
- 10 to 19 employees
- 20 to 99 employees
- 100 employees or more

3. Please rate the importance of the following characteristics at the time of specifying a construction material?

	Very Important	Important	Somewhat Important	Not at All important
Environmental performance				
Structural performance				
Economic performance				
Aesthetics				
Fire performance				
Earthquake performance				
Availability in the market				
Acoustic performance				
Cost of post-construction maintenance				
Durability				
LEED credits				
Other (please specify):				

4. How familiar are you with Cross-Laminated Timber (CLT), also known as "Cross-Lam," "X-Lam," or "Massive Timber"?

- Very familiar
- Somewhat familiar
- Not very familiar
- Have not heard about it

5. How did you hear about Cross-Laminated Timber (CLT) for the first time?

- Internet
- Television
- Newspaper
- Magazine
- Academic Journal
- Radio
- Relative or friend
- Conference/Seminar/Workshop
- Other (please specify)

6. Please rate the following features of Cross-Laminated Timber, compared to other materials (e.g. steel, concrete).

	Excellent	Good	Average	Below average	Poor	× Don't know
Environmental performance	◌	◌	◌	◌	◌	◌
Structural performance	◌	◌	◌	◌	◌	◌
Economic performance	◌	◌	◌	◌	◌	◌
Aesthetics	◌	◌	◌	◌	◌	◌
Fire performance	◌	◌	◌	◌	◌	◌
Earthquake performance	◌	◌	◌	◌	◌	◌
Acoustic performance	◌	◌	◌	◌	◌	◌
Cost of post-construction maintenance	◌	◌	◌	◌	◌	◌
Durability	◌	◌	◌	◌	◌	◌
LEED credits	◌	◌	◌	◌	◌	◌
Others (please specify) ______	◌	◌	◌	◌	◌	◌

7. If Cross-Laminated Timber (CLT) was available in the U.S., how likely are you to use CLT it in one of your building projects in the near future?

- ◌ Very likely
- ◌ Likely
- ◌ Uncertain
- ◌ Unlikely
- ◌ Very unlikely

8. Please indicate in what types of building you think CLT would be most appropriate as a construction system.

	Very appropriate	Somewhat appropriate	Not at all appropriate	× Don't know
Residential (single-family housing)	○	○	○	○
Residential (multi-family housing)	○	○	○	○
Commercial (e.g. retail stores, offices, restaurants, hotels, hospitals)	○	○	○	○
Educational (e.g.schools, universities, libraries, museums, theaters)	○	○	○	○
Governmental (e.g.city halls, courthouses, embassies)	○	○	○	○
Recreational (e.g. gymnasiums, stadiums, pools, ice rinks)	○	○	○	○
Industrial (e.g. factories, storage)	○	○	○	○
Transport (e.g. airports, bus stations)	○	○	○	○
Other (please specify):	○	○	○	○

9. Which do you think are the most important barriers to adoption of Cross-Laminated Timber in the U.S.?

	Large Barrier	May be a barrier	Not a barrier at all
Amount of wood required	○	○	○
Availability in the market	○	○	○
Initial Cost	○	○	○
Availability of technical information	○	○	○
Compatibility with Building Code	○	○	○
Other (please specify):	○	○	○

10. The current State-by-State Building Codes in the U.S. limit wood construction to 5 to 6 stories. If the code changes, allowing higher buildings to be built with CLT, do you believe Cross-Laminated Timber will be used as a construction system for buildings over 6 stories in the U.S.?

- ○ Very likely
- ○ Likely
- ○ Uncertain
- ○ Unlikely
- ○ Very unlikely (please, explain why)

11. Other comments you may want to add?

12. If you would like to receive a report of the results of this study, please enter your email address below.

Appendix 3

IRB Approval

Fri, Oct 11, 2013 at 10:58 AM

Cynthia McGill <mcgil018@umn.edu>
To: María Laguarda <lagua006@umn.edu>, Jeffery Perkey <perke001@umn.edu>

Maria,

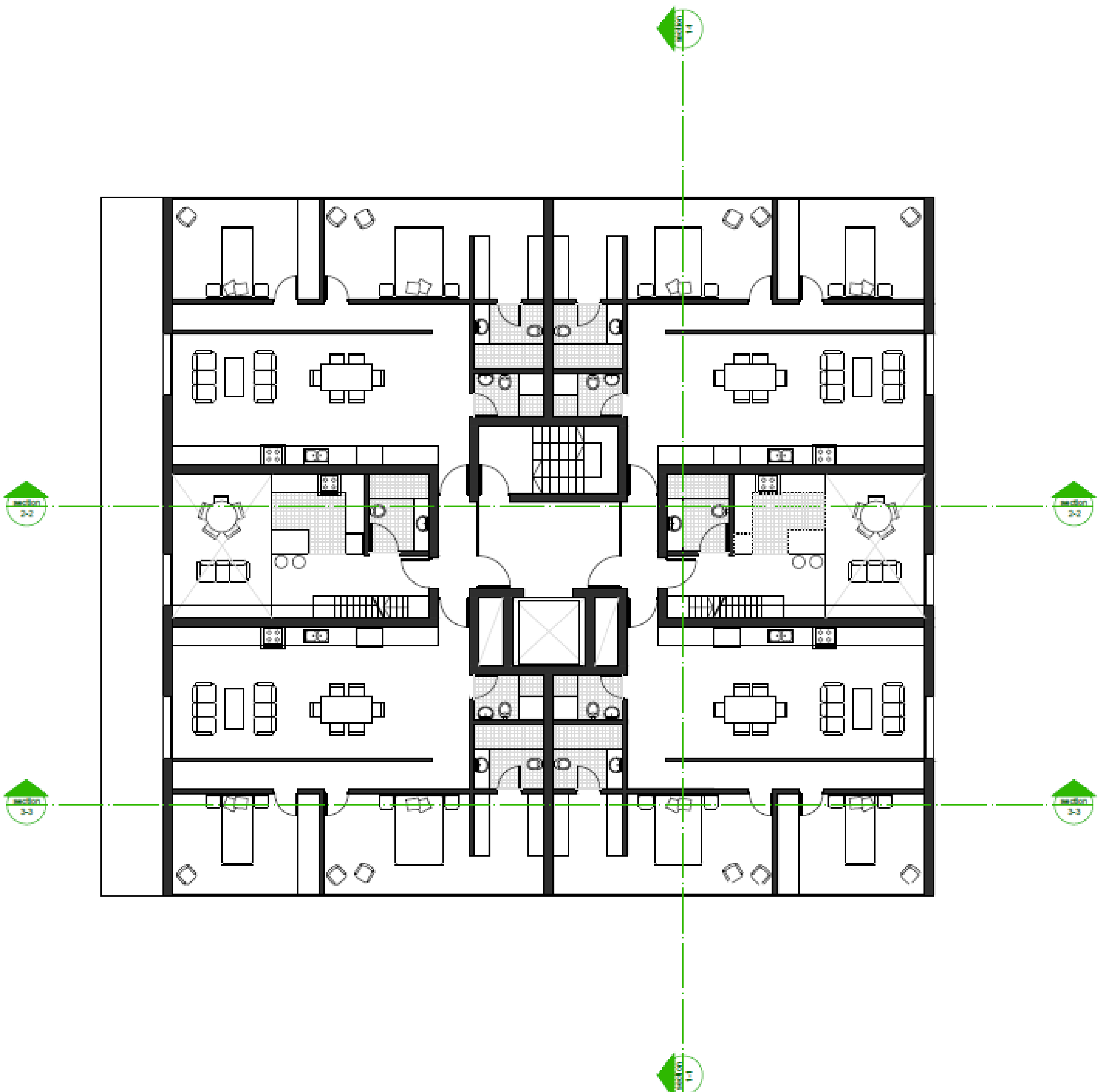
Thank you for your question.
I have reviewed the survey introduction and the survey questions and determined that the work described research does not meet the federal definition of human subject research and will not require an IRB review.
All of your questions have to do with industrial perception of a new product not any private or personal information.

Best wishes on your research project.
Cynthia

--
Cynthia McGill, CIP
Assistant Director
Human Research Protection Program
University of Minnesota
mcgil018@umn.edu
Direct 612-626-5827
Main Line 612-626-5654

Appendix 4

Floor plans



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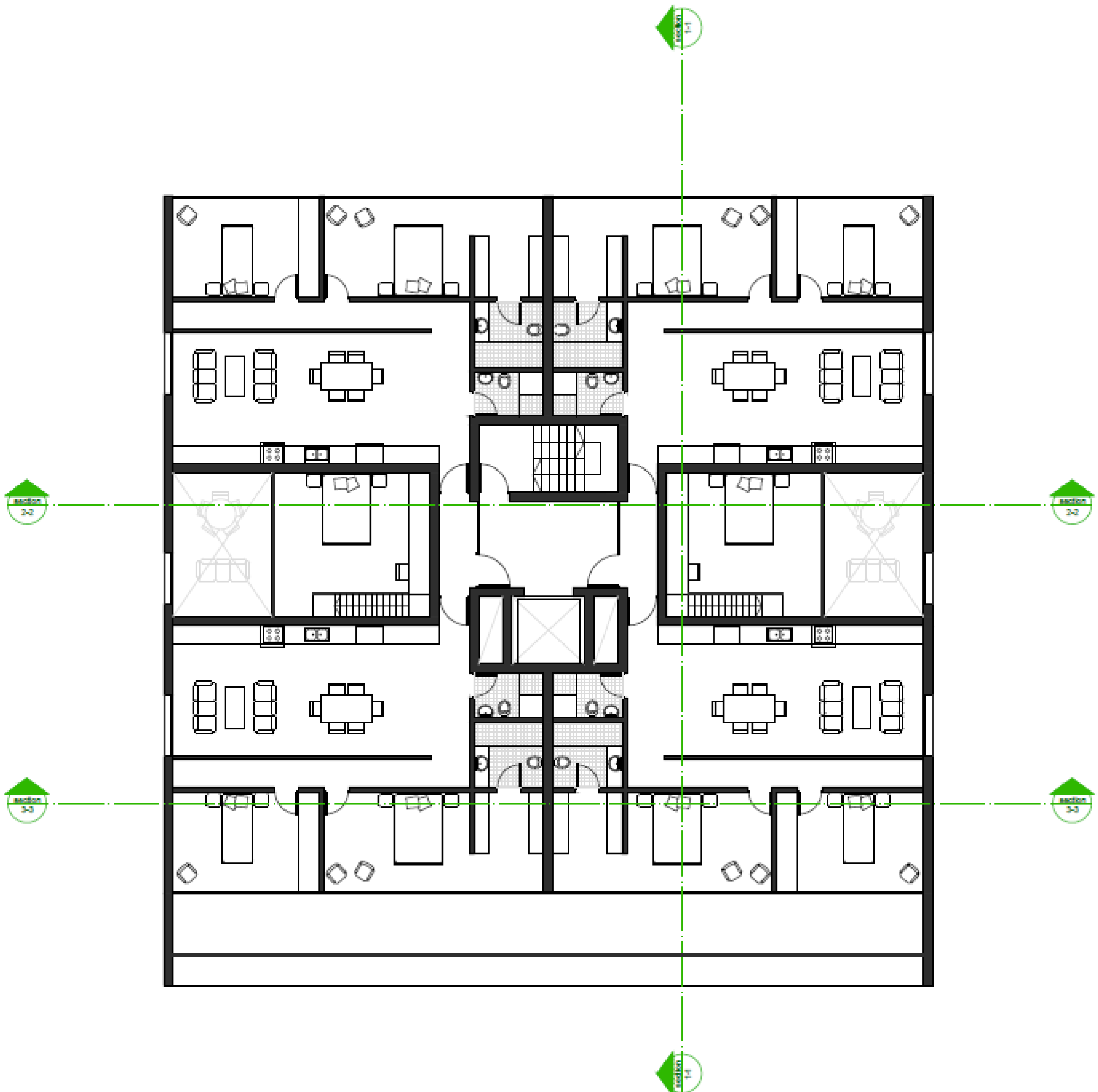

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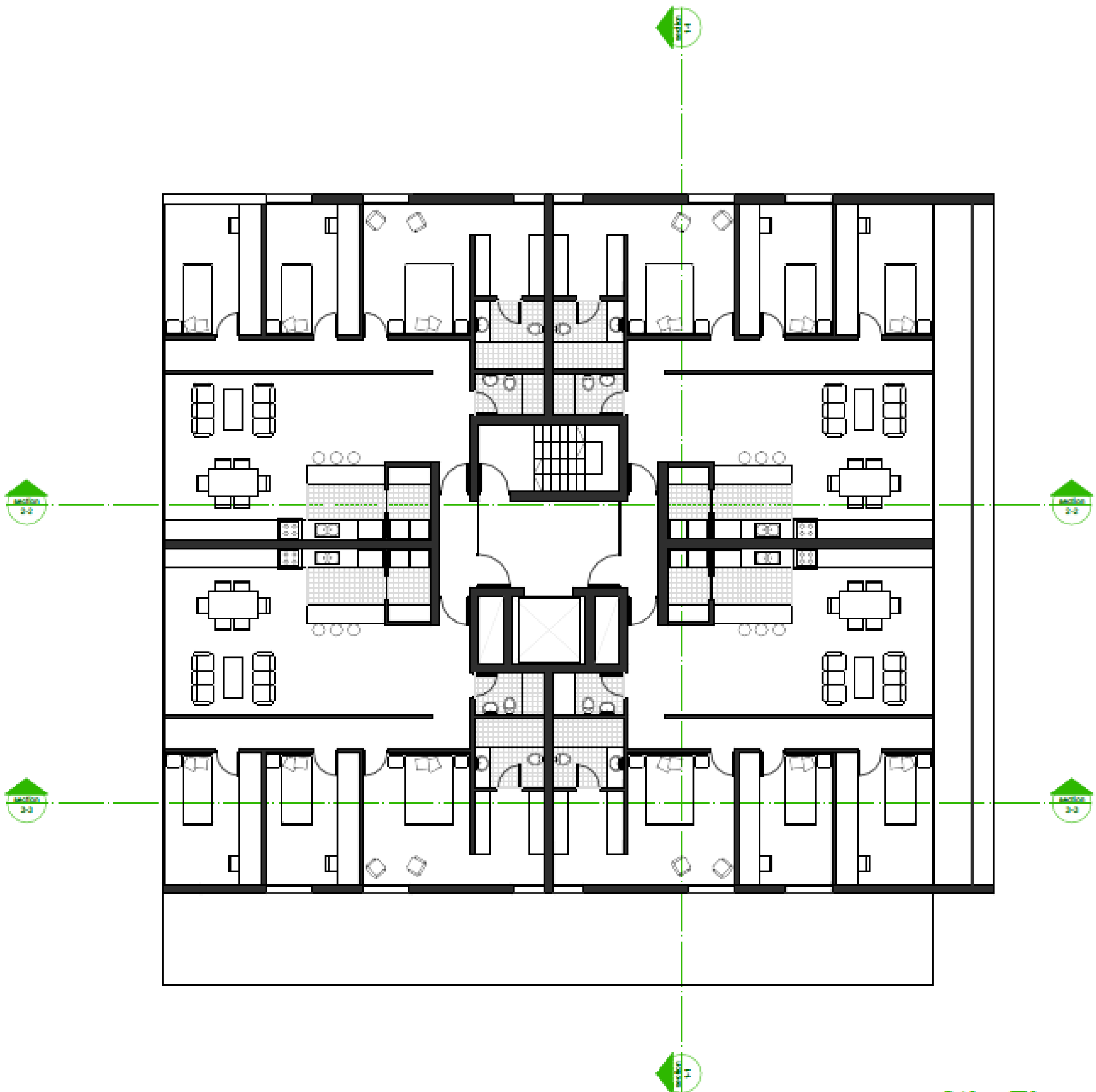

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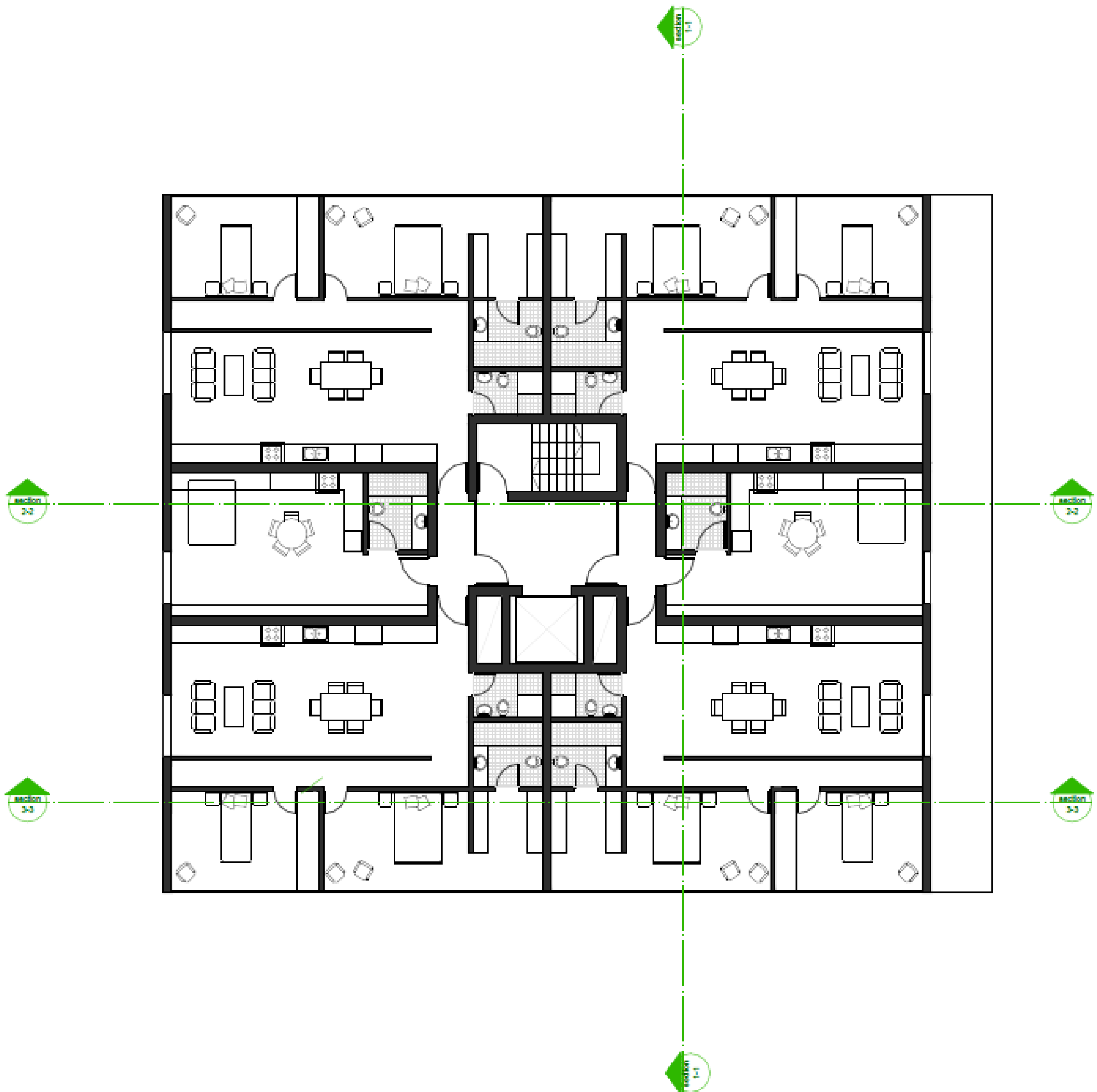

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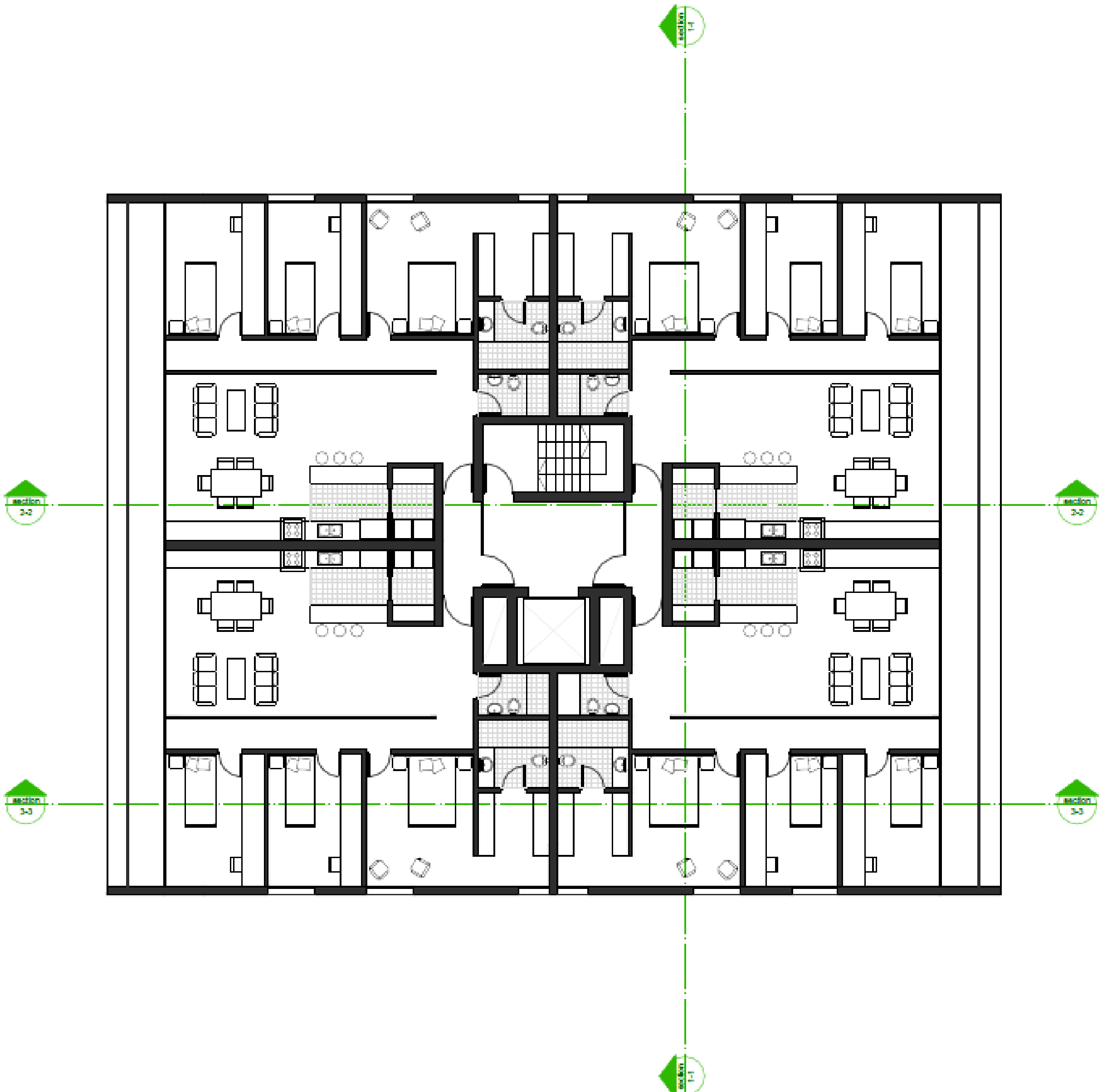

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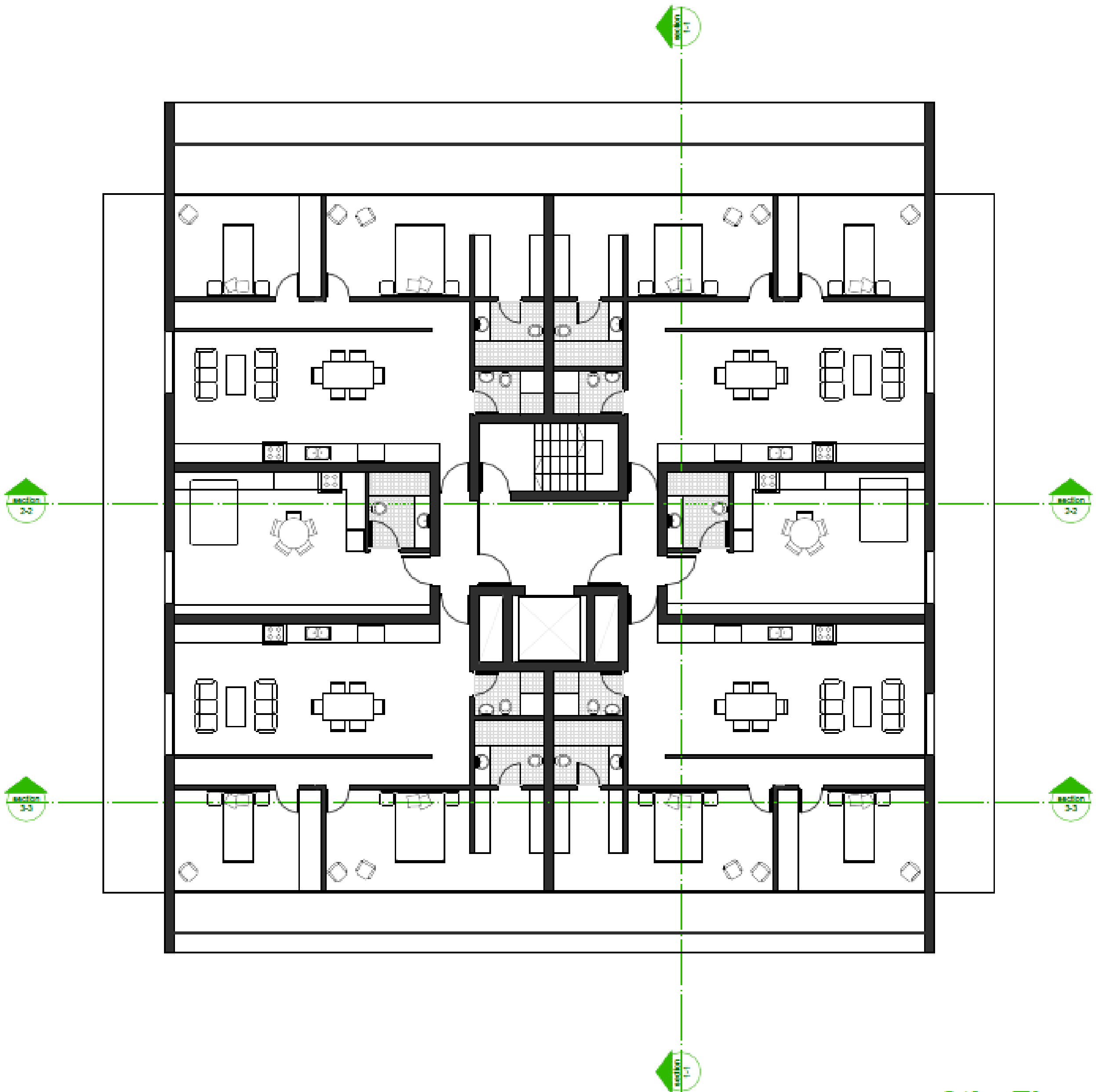
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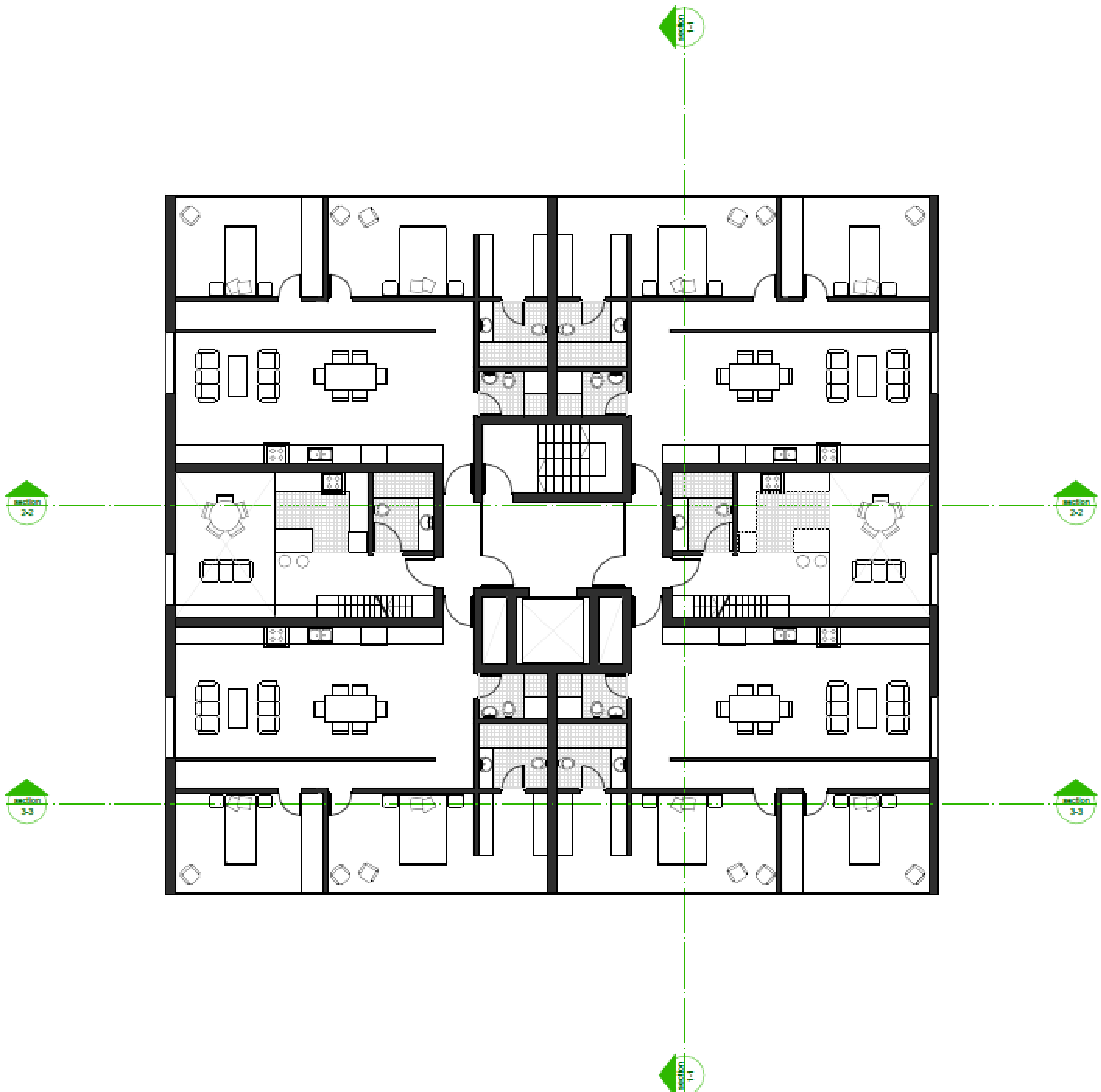
9th. Floor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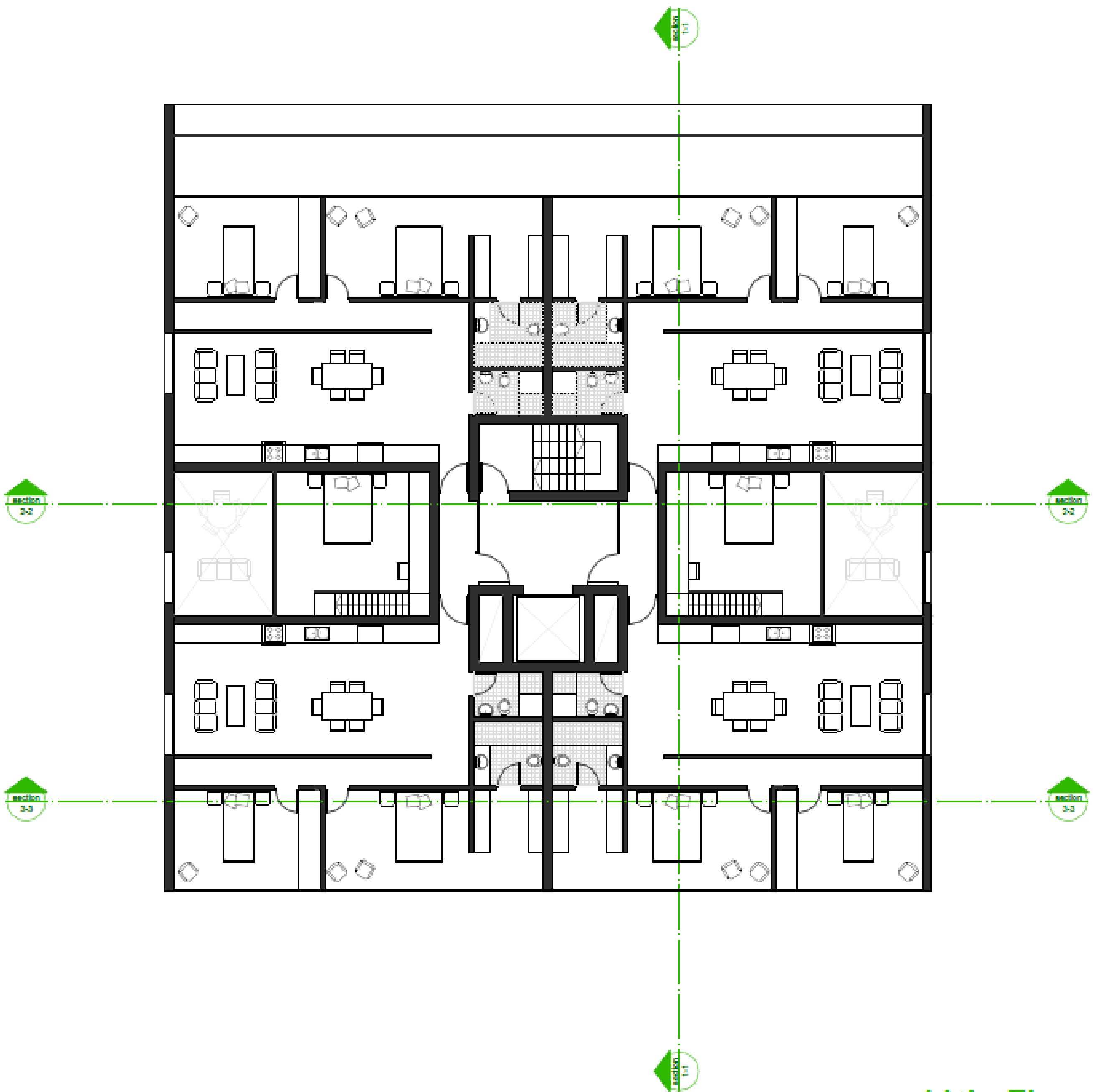
10th. Floor



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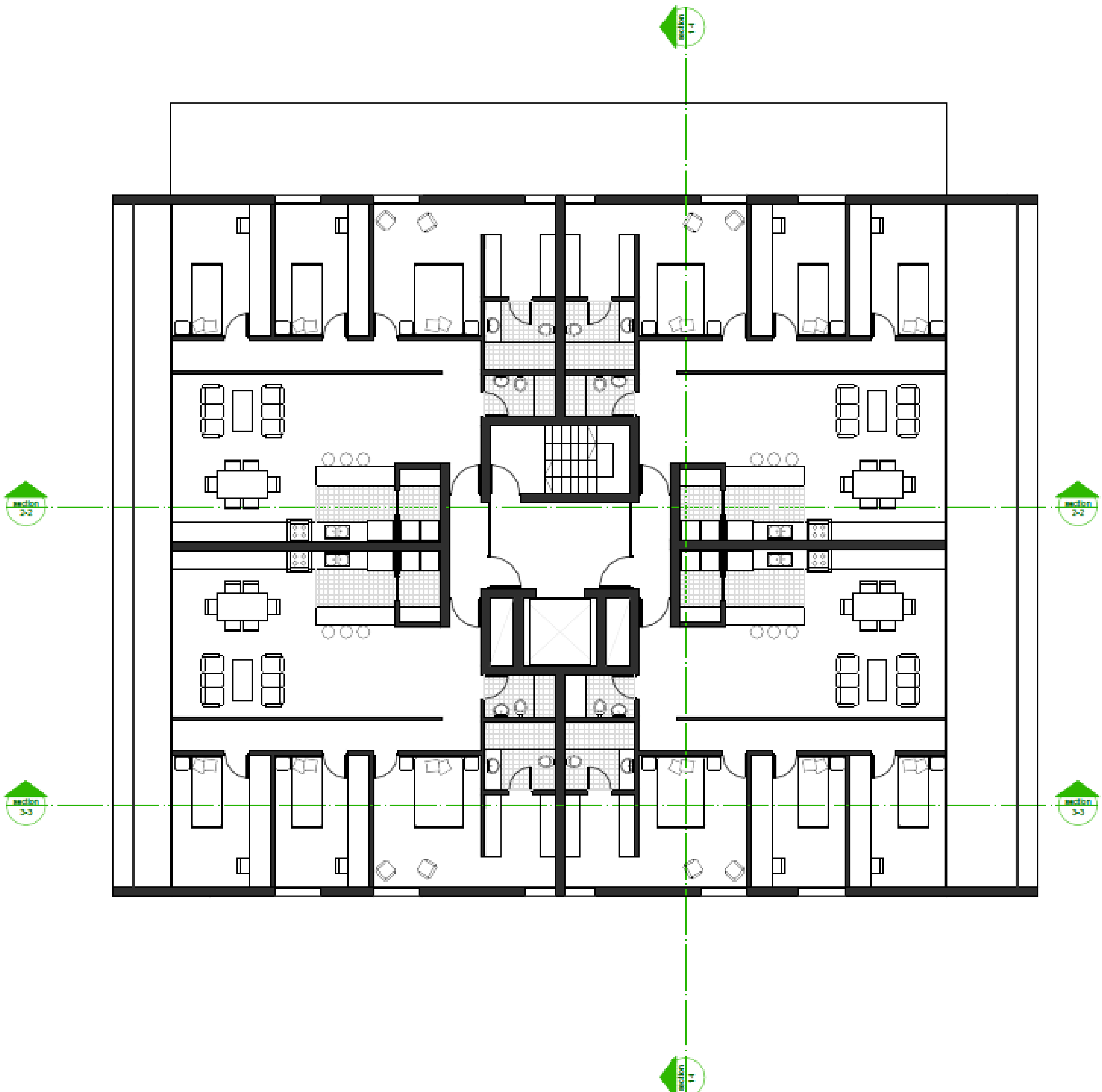
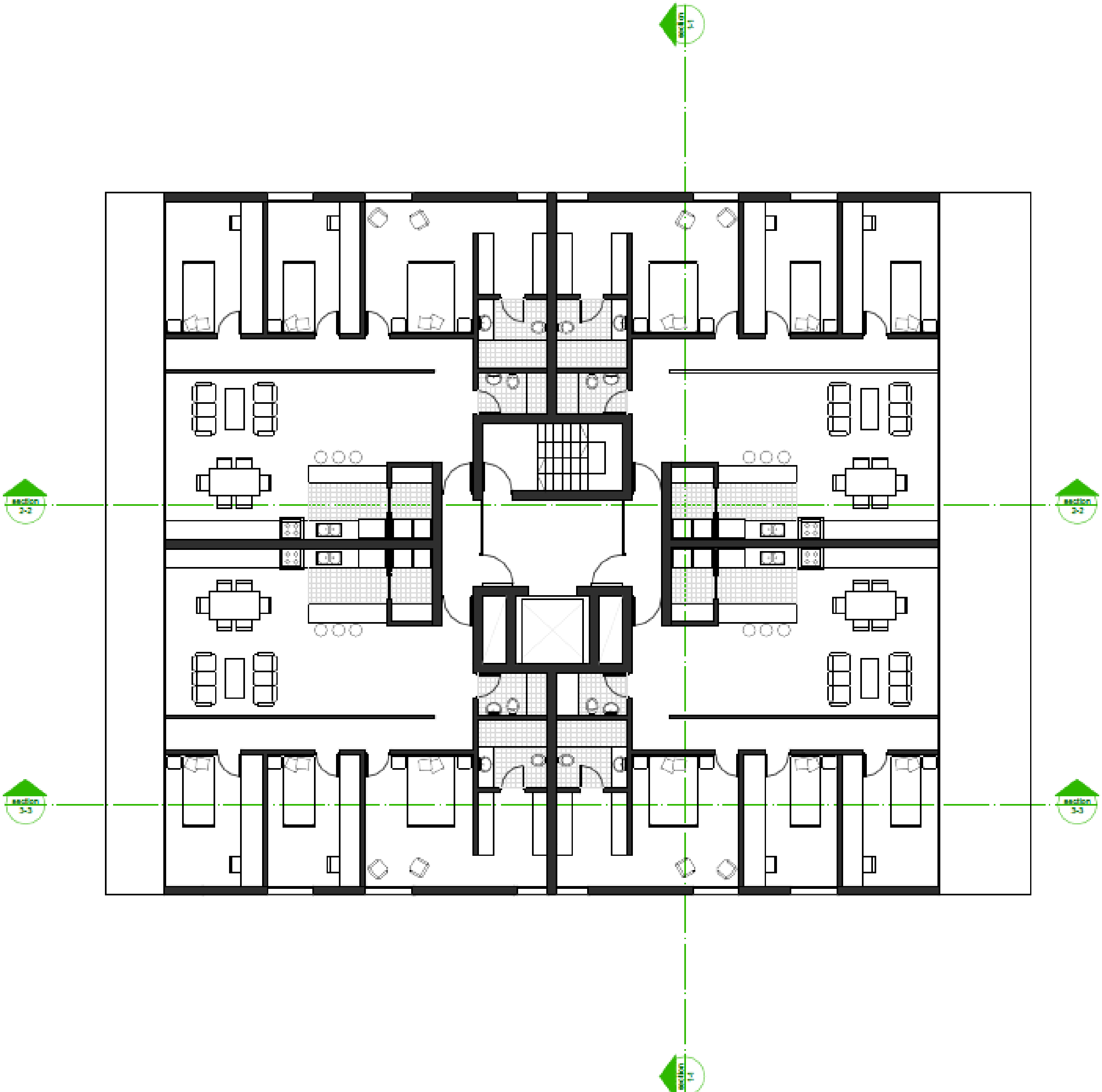


12th. Floor



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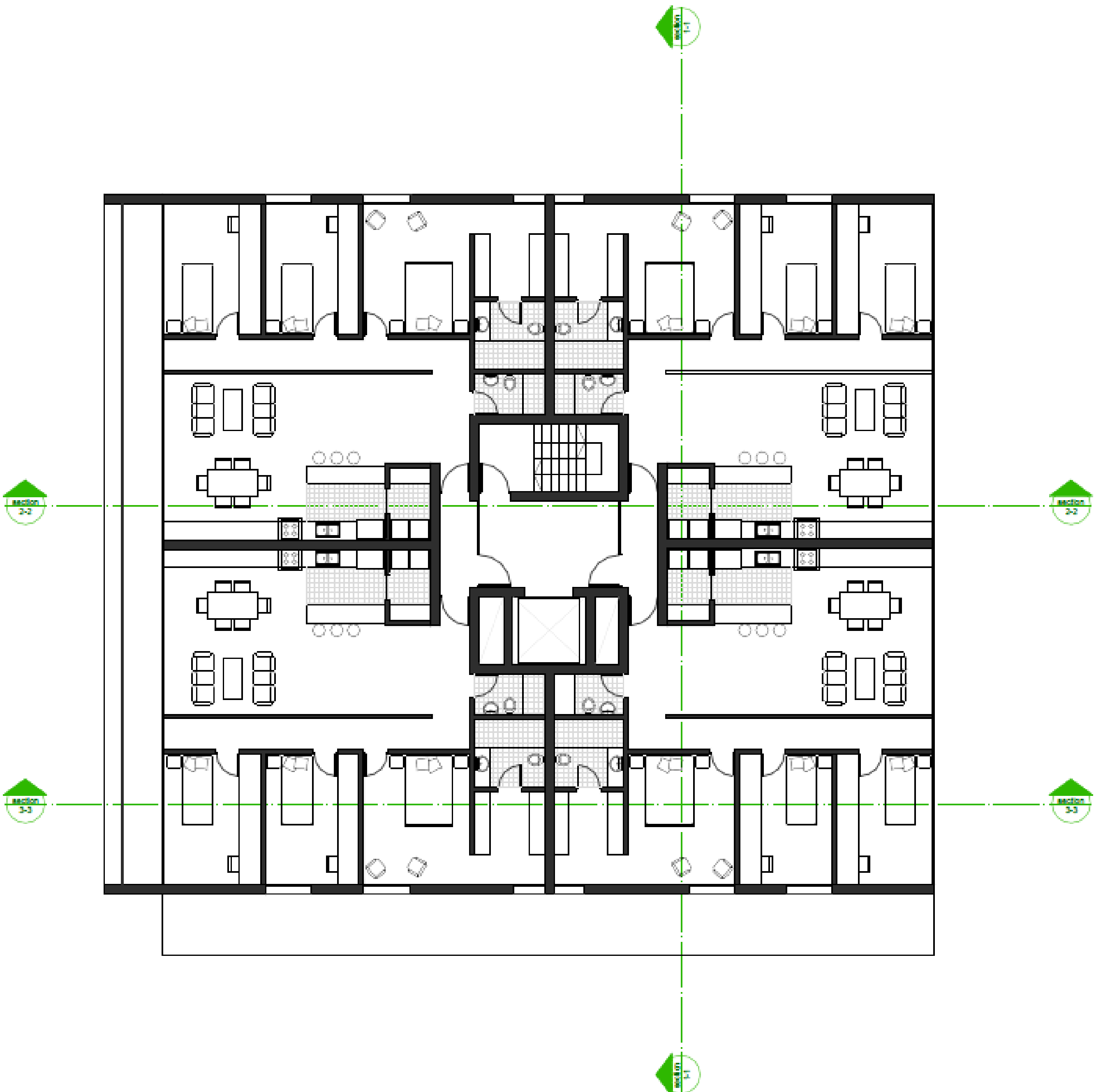
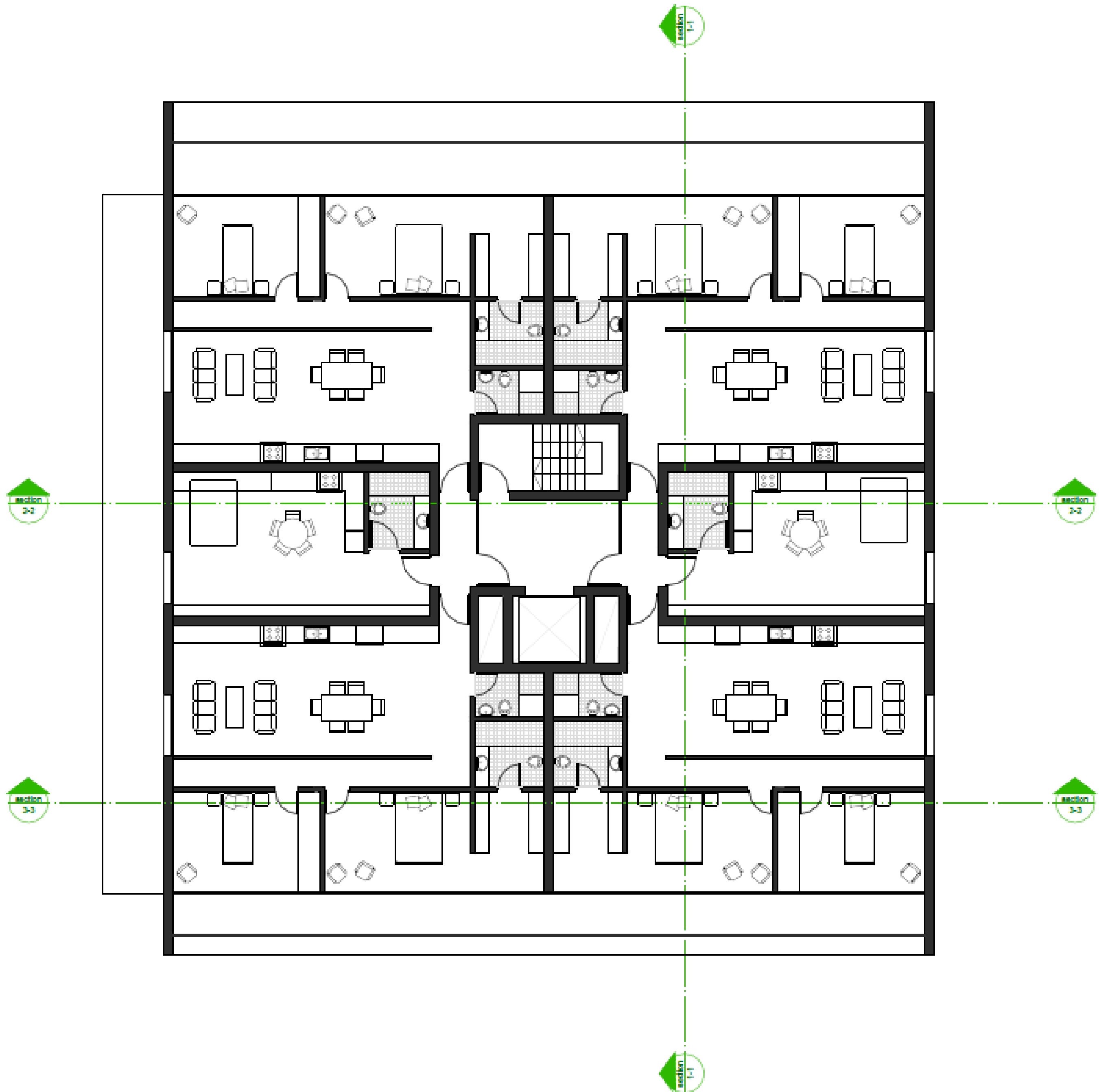
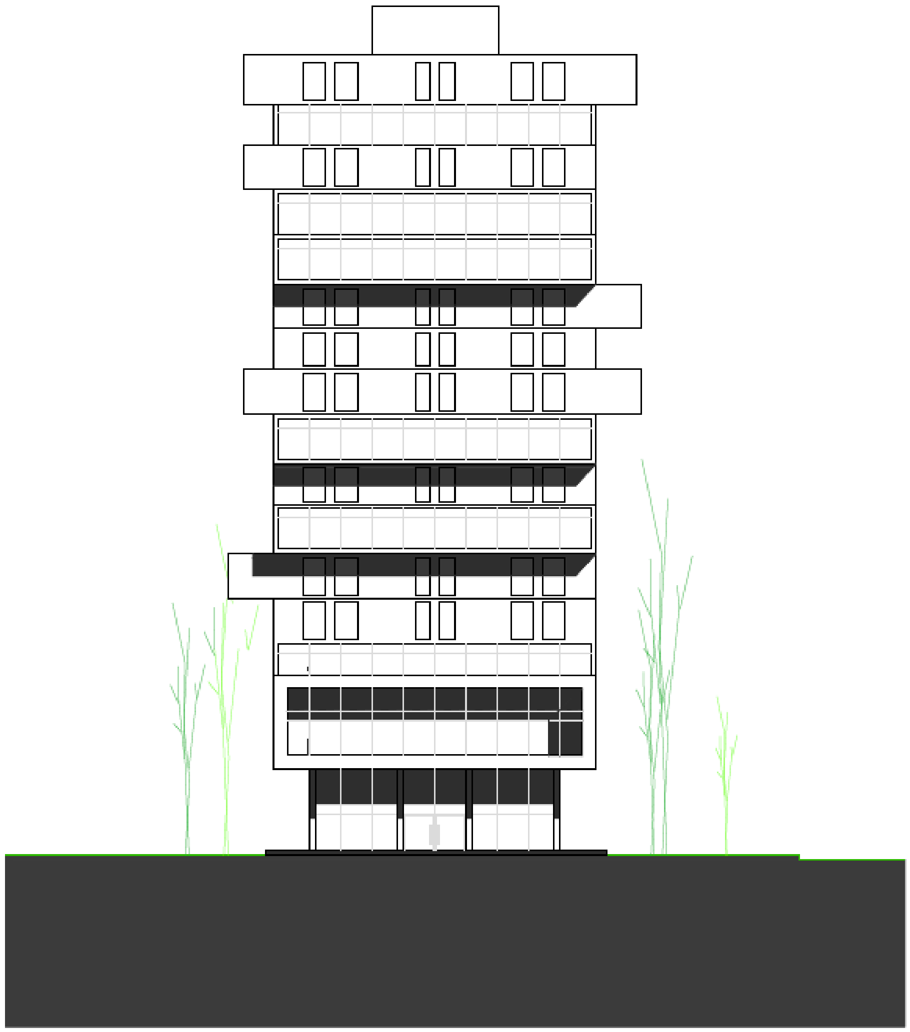


15th. Floor

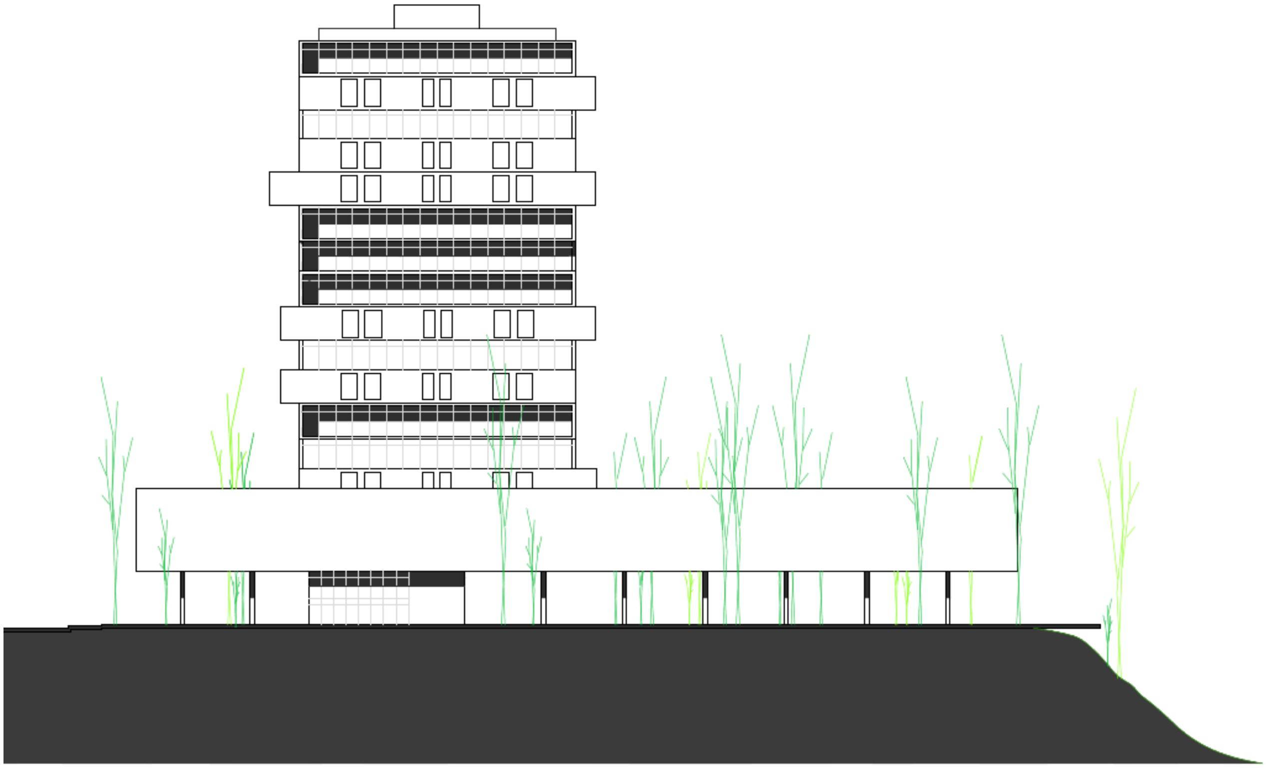


16th. Floor

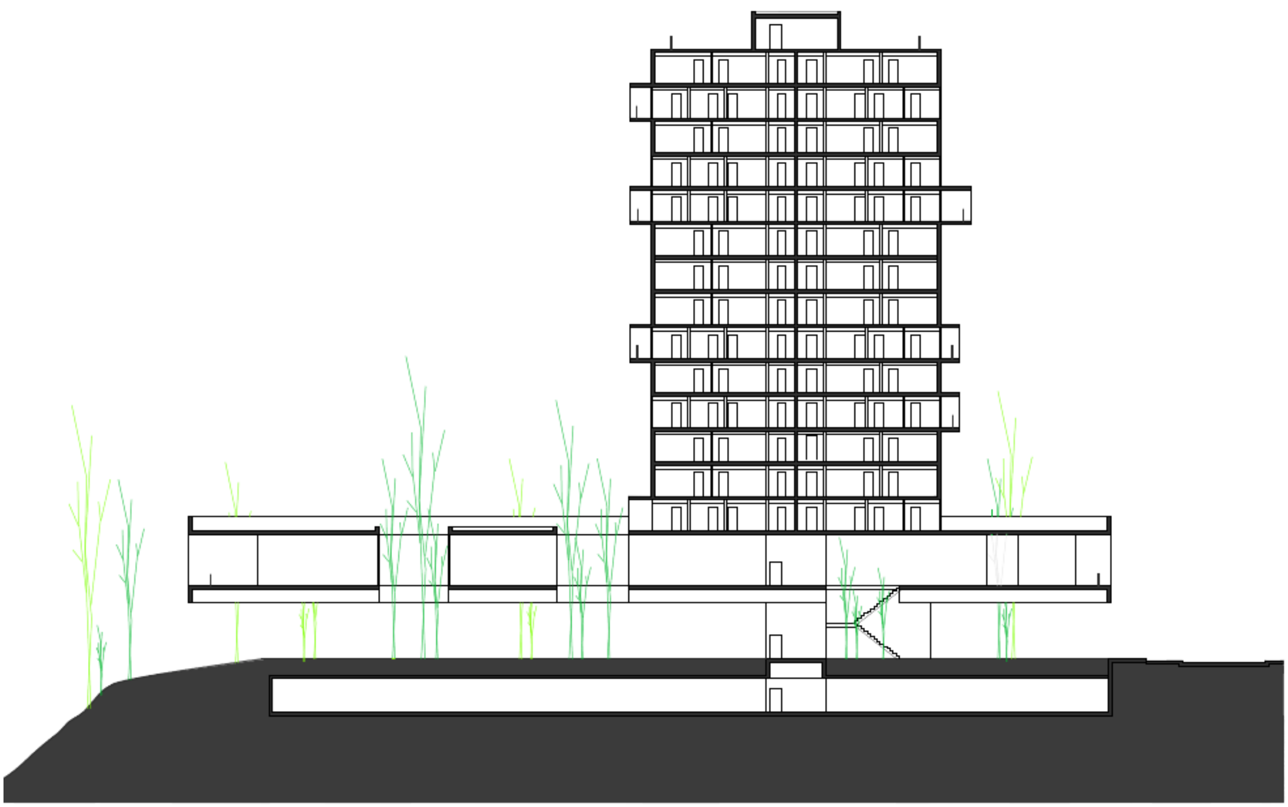
Elevations and sections



Northeast Elevation



Northwest Elevation



Section 3-3